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## Practical Issues in Floodplain Mapping Over Large Regions

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A thesis submitted in partial fulfillment of the requirements for the Master of Engineering  
Science degree in Civil and Environmental Engineering

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## Abstract

Flooding events are among the costliest and most frequent natural hazards occurring in Canada. Floodplain mapping is a non-structural flood management strategy that involves the formulation of hydrologic and hydraulic models to produce maps which predict extent and depth of floods. Practices and availability of floodplain mapping vary across Canada. The current state of floodplain mapping across Canada has been identified and reviewed. Vast areas of flood prone regions across Canada have been identified as not having floodplain maps or lacking updated ones. Large region floodplain maps have been recently introduced and can cover national and global regions. Limitations of spatial resolution exist in large region mapping efforts, which hinder their implementation for local scale floodplain management practices. A recent study at Western University produced a national floodplain map with a spatial resolution of 1 km x 1 km. This national floodplain map is highly accurate; however, spatial resolution needs to be improved to be implemented within local scale floodplain studies. The study presented in this thesis developed a downscaling methodology to further improve spatial resolution of the floodplain map. The downscaling methodology was implemented to produce floodplain maps at spatial resolutions of 20m, 40m, 60m, 80m, 100m, 200m, 300m, and 400m for two case study river basins: Bow and Elbow River Basin and St John River Basin. Analysis of the floodplain maps was completed, followed by volume conservation and computational time studies to assess the accuracy of the proposed downscaling methodology and to compare the sensitivity of the downscaling methodology.

**Keywords:** Flooding, Floodplain Mapping, Global Flood Models, Downscaling, Spatial Resolution.



## **Summary for Lay Audience**

Flooding is a regularly occurring event that accounts for large economic losses and insurance claims every year. Floodplain maps are a floodplain management tool designed to derive the extent of historic and projected flooding events. The floodplain maps are used to limit development within flood prone regions and to identify population, property, and infrastructure exposure, in the event of future flooding events. Provincial and territorial governments in Canada are responsible for the production of floodplain maps within their respective jurisdictions. Floodplain mapping practices vary across Canada, depending on the standards used to derive the extent of flooding and the availability of floodplain maps. The current state of floodplain mapping practices across Canada is reviewed here, as also the present issues with the availability and maintenance of maps for flood prone regions. Recently developed large region maps reflect floodplains at national, continental, and global regions and these can be created within a reasonable time period. A study conducted at Western University presented a framework for the production of a national floodplain map for Canada that was then used to identify population exposure across the country. However, the spatial resolution of many floodplain maps that cover large regions, including the national floodplain map produced by Western University, is approximately 1 km only due to computational limitations. This resolution is impractical for local scale studies and further improvement in resolution is required through downscaling. Common floodplain mapping downscaling methods were compared in this study and a methodology produced to improve the resolution of national floodplain maps. The downscaling methodology was performed to produce floodplain maps at resolutions of 20m, 40m, 60m, 80m, 100m, 200m, 300m, and 400m for two case study areas: Bow and Elbow River Basin and St John River Basin. The methodology depends on the practical utility of the map for local scale studies, the percentage volume of water conserved in downscaling, and overall computational time. The downscaled 100 m floodplain map is able to effectively predict property and infrastructure exposure and can be produced within an optimal computational time, thus reflecting its feasibility within local floodplain management strategies.

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## Table of Contents

<b><i>Abstract.....</i></b>	<b><i>i</i></b>
<b><i>Summary for Lay Audience.....</i></b>	<b><i>ii</i></b>
<b><i>Acknowledgements.....</i></b>	<b><i>iii</i></b>
<b><i>Table of Contents .....</i></b>	<b><i>iv</i></b>
<b><i>List of Figures .....</i></b>	<b><i>vii</i></b>
<b><i>List of Tables .....</i></b>	<b><i>x</i></b>
<b><i>List of Appendices.....</i></b>	<b><i>xi</i></b>
<b><i>1. Introduction.....</i></b>	<b><i>1</i></b>
1.1 Flooding.....	1
1.2 Floodplain Mapping.....	3
1.3 Large Region Floodplain Mapping.....	4
1.4 Scale Issues in Large Region Floodplain Mapping .....	6
1.5 Research Objectives.....	7
<b><i>2. Floodplain Mapping in Canada .....</i></b>	<b><i>9</i></b>
2.1 Federal Flood Damage Reduction Program .....	9
2.2 Current Status of Floodplain mapping in Canada.....	10
2.2.1 British Columbia .....	11
2.2.2 Alberta.....	14
2.2.3 Saskatchewan .....	16
2.2.4 Manitoba .....	17
2.2.5 Ontario .....	18
2.2.6 Quebec .....	21
2.2.7 New Brunswick.....	23
2.2.8 Newfoundland and Labrador .....	25
2.2.9 Nova Scotia .....	27

2.2.10	Prince Edward Island .....	29
2.2.11	Northwest Territories .....	30
2.2.12	Nunavut .....	31
2.2.13	Yukon .....	32
2.3	Federal Flood mapping Guideline Series .....	32
2.4	Discussion .....	35
<b>3.</b>	<b><i>Global Flood Models .....</i></b>	<b>41</b>
3.1	Description of Global Flood Models .....	41
3.2	Data for Global Flood Models .....	42
3.3	Existing Global Flood Models .....	43
3.4	CaMa-Flood Hydrodynamic Model for Canada .....	43
3.5	Resolution Issues .....	47
<b>4.</b>	<b><i>Description of Floodplain Mapping Downscaling Methodologies .....</i></b>	<b>50</b>
4.1	GLOFRIS Downscaling Methodology .....	50
4.2	Fathom-US Downscaling Methodology .....	52
4.3	Sub-grid Two-Tiered Downscaling Methodology .....	53
4.4	Discussion of Downscaling Methodologies .....	54
<b>5.</b>	<b><i>Implementation of Downscaling for National Floodplain Map .....</i></b>	<b>56</b>
5.1	Study Areas .....	56
5.1.1	Calgary Case Study .....	56
5.1.2	New Brunswick Case Study .....	58
5.2	Data Requirements .....	59
5.3	Downscaling Methodology .....	60
5.3.1	Data Pre-Processing .....	62

5.3.2	Downscaling Methodology .....	63
5.3.3	Post-Processing of the Downscaled Data.....	64
5.4	Illustrative Downscaling Methodology Example .....	66
<b>6.</b>	<b><i>Results and Discussion .....</i></b>	<b>73</b>
6.1	Spatial Resolutions .....	74
6.2	Downscaled Floodplain Mapping.....	78
6.2.1	Calgary Case Study Results .....	82
6.2.2	New Brunswick Case Study Results .....	89
6.3	Conservation of Flood Volume Analysis .....	95
6.4	Flood Depth Difference Analysis .....	99
6.5	Computational Time Requirements.....	103
<b>7.</b>	<b><i>Conclusion .....</i></b>	<b>106</b>
<b>8.</b>	<b><i>References .....</i></b>	<b>110</b>
<b>9.</b>	<b><i>Appendices .....</i></b>	<b>123</b>

## List of Figures

Figure 1: iMapBC application presenting the floodplain maps for the Chilliwack and Vedder rivers (Government of British Columbia, n.d.) .....	13
Figure 2: Fraser River Council 100-year design flood for 2100 climate change scenario with 1m sea level rise (Fraser River Council, 2019) .....	13
Figure 3: Flood Hazard Map Application Alberta presenting the derived floodway (dark red) and flood fringe (light red) for the flood hazard area (Government of Alberta, 2019) .....	15
Figure 4: TRCA Interactive Floodplain Map ( <a href="https://trca.ca/conservation/flood-risk-management/flood-plain-map-viewer/">https://trca.ca/conservation/flood-risk-management/flood-plain-map-viewer/</a> ) .....	20
Figure 5: Floodplain map presenting the regulatory floodplain and limit for Constance Creek in the Mississippi Valley Conservation Authority ( <a href="https://mvc.on.ca/development-permits/flood-prone-areas-and-map/constance-creek/">https://mvc.on.ca/development-permits/flood-prone-areas-and-map/constance-creek/</a> ) .....	21
Figure 6: “Zone d’intervention spéciale” presents the delineated flood zone that resulted from the spring floods of 2017 and 2019 (Gouvernement du Québec, 2019) .....	23
Figure 7: GeoNB interactive online floodplain map that presents the 2018 Lower Saint John River floods. The blue outline represents the extent of the flood event (GeoNB, 2018) .....	24
Figure 8: Historical floodplain map drawing for the Lower Marsh Creek flood risk area (Government of New Brunswick, 1979).....	25
Figure 9: 1:20 and 1:100 Annual Exceedance Probability climate change flood lines using the 2050 maximum IDF relationship for Corner Brook (Government of Newfoundland and Labrador, 2013).....	27
Figure 10: City of Halifax Floodplain Map that presents the floodway (blue) and flood fringe (purple) for the Sackville Region (City of Halifax, 2017) .....	28
Figure 11: ACASA produced 2050 hazard floodplain map for the community of Mount Stewart. The map presents the extent of flooding resulting from conditions involving a 50 cm sea level rise (green), and 1 in 10-year (yellow), 1 in 25-year (orange), 1 in 50-year (red) and 1 in 100-year (brown) storm surge (ACASA, 2012).....	30
Figure 12: ATLAS Interactive Floodplain Map presenting the flood risk area for Fort Simpson (ATLAS, 2017).....	31

Figure 13: Flood Mapping Framework established by NRCAN (NRCAN, 2018a).....	33
Figure 14: Mohanty and Simonovic (2020a) National Floodplain Mapping Framework	47
Figure 15: Boundary of the Calgary Case Study .....	57
Figure 16: Boundary for the New Brunswick Case Study.....	58
Figure 17: Implemented Downscaling Framework .....	61
Figure 18: Selected region for the illustrative downscaling process. The selected region is highlighted in yellow. ....	66
Figure 19: Clipped Digital Elevation Model for the selected region.....	67
Figure 20: Clipped low-resolution floodplain map for the selected region.....	68
Figure 21: Clipped water surface level map for the selected region.....	68
Figure 22: Downscaled floodplain map following equation 1 for the selected region.....	69
Figure 23: Downscaled flood depths following the water depth constricting the maximum flood depth for the selected region.....	70
Figure 24: Downscaled flood depths following the adjacent flood cell condition in equation 3.....	71
Figure 25: Final downscaled flood depths following the mass conservation step for the selected region with a colour scale. ....	72
Figure 26: Cross-section comparison presenting elevation data for the different spatial resolutions.....	75
Figure 27: 500 m spatial resolution grid cell. The colour represents the single flood depth for the 500 m cell. ....	76
Figure 28: 100 m spatial resolution grid cells within one 500 m spatial resolution grid cell. The colours represent the flood depth for each 100m cell. Red Cells represent no flooding, while the remaining coloured cells represent flooded cells with varying depths. All white cells occupy no flood depth values. ....	77
Figure 29: 20 m spatial resolution grid cells within one 500 m input spatial resolution grid cell. The colours represent the flood depth for each 20m cell. Red cells represent no flooding, while blue cells represent flooded cells. All white cells occupy no flood depth values. ....	77
Figure 30: 100-year low-resolution floodplain map for Calgary.....	79
Figure 31: 200-year low-resolution floodplain map for Calgary.....	80

Figure 32: 100-year low-resolution floodplain map for New Brunswick.....	81
Figure 33: 200-year low-resolution floodplain map for New Brunswick.....	82
Figure 34: Downscaled 100m resolution floodplain for Calgary 100-year flood.....	85
Figure 35: Downscaled 100m resolution floodplain map for Calgary 200-year flood.....	86
Figure 36: Downscaled 100m resolution floodplain map for Calgary 100-year flood presenting the confluence of the Bow and Elbow Rivers .....	87
Figure 37: Low-resolution floodplain map for Calgary 100-year flood presenting the confluence of the Bow and Elbow Rivers.....	87
Figure 38: Downscaled 100m resolution floodplain map for Calgary 200-year flood presenting the confluence of the Bow and Elbow Rivers .....	88
Figure 39: Low-resolution floodplain map for Calgary 200-year flood presenting the confluence of the Bow and Elbow Rivers.....	88
Figure 40: Downscaled 100 m resolution floodplain map for New Brunswick 100-year flood .....	91
Figure 41: Downscaled 100 m resolution floodplain map for New Brunswick 200-year flood .....	92
Figure 42: Region A downscaled 100 m resolution floodplain map for New Brunswick 100-year flood.....	93
Figure 43: Region A low-resolution floodplain map for New Brunswick 100-year flood	93
Figure 44: Region B downscaled 100 m resolution floodplain map for New Brunswick 100-year flood.....	94
Figure 45: Region B low-resolution floodplain map for New Brunswick 100-year flood	94
Figure 46: Volume conservation for downscaling methodology.....	97
Figure 47: Volume Conservation following the identification of neighbouring flooded cells .....	99
Figure 48: Flood Depth Difference Map between the Low-Resolution floodplain map and 100 m downscaled floodplain map for the 100-year flood event in Calgary.....	101
Figure 49: Flood Depth Difference Map between the Low-Resolution floodplain map and 100 m downscaled floodplain map for the 100-year flood event in New Brunswick ....	102



## **List of Tables**

Table 1: Summary of Floodplain Mapping Practices Across Canada .....	37
Table 2: Summary of the location for each floodplain map and their respective spatial resolution.....	73
Table 3: Volume conservation estimates for the downscaled floodplain maps following the downscaling methodology .....	96
Table 4: Volume conservation accuracies for the downscaled floodplain maps following the identification of neighbouring flooded cells .....	98
Table 5: Computational Time Study for Calgary .....	104
Table 6: Computational Time Study for New Brunswick .....	105

## List of Appendices

<b>Appendix A: Summary of Ontario Conservation Authority Floodplain Practices .....</b>	<b>123</b>
<b>Appendix B: Matlab Scripts for Downscaling .....</b>	<b>128</b>
<b>Appendix C: Calgary Floodplain Maps.....</b>	<b>135</b>
Appendix C.1: 20m 100 year Floodplain Map .....	135
Appendix C.2: 20m 200 year Floodplain Map .....	136
Appendix C.3: 40m 100 year Floodplain Map .....	137
Appendix C.4: 40m 200 year Floodplain Map .....	138
Appendix C.5: 60m 100 year Floodplain Map .....	139
Appendix C.6: 60m 200 year Floodplain Map .....	140
Appendix C.7: 80m 100 year Floodplain Map .....	141
Appendix C.8: 80m 200 year Floodplain Map .....	142
Appendix C.9: 100m 100 year Floodplain Map .....	143
Appendix C.10: 100m 200 year Floodplain Map .....	144
Appendix C.11: 200m 100 year Floodplain Map .....	145
Appendix C.12: 200m 200 year Floodplain Map .....	146
Appendix C.13: 300m 100 year Floodplain Map .....	147
Appendix C.14: 300m 200 year Floodplain Map .....	148
Appendix C.15: 400m 100 year Floodplain Map .....	149
Appendix C.16: 400m 200 year Floodplain Map .....	150
<b>Appendix D: New Brunswick Floodplain Maps .....</b>	<b>151</b>
Appendix D.1: 20m 100 year Floodplain Map .....	151
Appendix D.2: 20m 200 year Floodplain Map .....	153
Appendix D.3: 40m 100 year Floodplain Map .....	155

Appendix D.4: 40m 200 year Floodplain Map .....	157
Appendix D.5: 60m 100 year Floodplain Map .....	159
Appendix D.6: 60m 200 year Floodplain Map .....	161
Appendix D.7: 80m 100 year Floodplain Map .....	163
Appendix D.8: 80m 200 year Floodplain Map .....	165
Appendix D.9: 100m 100 year Floodplain Map .....	167
Appendix D.10: 100m 200 year Floodplain Map .....	169
Appendix D.11: 200m 100 year Floodplain Map .....	171
Appendix D.12: 200m 200 year Floodplain Map .....	173
Appendix D.13: 300m 100 year Floodplain Map .....	175
Appendix D.14: 300m 200 year Floodplain Map .....	177
Appendix D.15: 400m 100 year Floodplain Map .....	179
Appendix D.16: 400m 200 year Floodplain Map .....	181

## **1. Introduction**

### **1.1 Flooding**

Flooding occurs when land that is typically dry becomes temporarily inundated by water (NRCAN, 2018a). Flooding events are among the most common and frequent natural hazards, disrupting livelihoods, crippling infrastructure, and causing loss of life. The three most common types of flood events are: fluvial flooding, which occurs when water level in a river, lake, or stream rises and overflows into the surrounding land; coastal flooding, which occurs when land areas along the coastal front are inundated due to storm surges and tsunamis; and pluvial flooding, which occurs when extreme precipitation events produce a flood independent of an overflowing water body (Zurich, 2020). Annually, 29% of the global population faces the risk of flooding from a 1 in 100-years flood event (Rentschler & Salhab, 2020). Between 2000 to 2019, global flooding events impacted over 4.2 billion people, cost US\$ 2.97 trillion, and resulted in 1.23 million lives being lost (UNDRR, 2020). The levels of risk and vulnerability as a result of flooding events will continue to heighten in the future due to factors spurred by accelerating socioeconomic growth and the increasing impacts of climate change (IPCC, 2012; Hemmati et al., 2020). Socioeconomic growth is promoting trends of urbanisation that lead to changes in land use conditions, which are resulting in flooding events with higher peak flows (Debbage & Shepherd, 2018; Hemmati et al., 2020). Climate change is seeing impacts of heavier precipitation, more frequent hurricane events, and a rise in sea levels that will increase both the velocity of flood flows as well as the height of the global sea level (Denchak, 2019).

Flooding events occur annually in Canada due to processes involving snowmelt runoff, intense precipitation events, ice jams, failure of dams, and coastal flooding resulting from storm surges, hurricanes, and tsunamis (Buttle et al., 2016). Fluvial flooding is the most common natural hazard event that impacts Canada and has caused the highest aggregate economic damage when compared to other hazard events (Kovacs & Sandik, 2013; NRCAN, 2018; IBC, 2019). Canada in its history has observed many severe floods across all provinces and territories. Notable historical flooding events that have occurred in Canada and the total damage they caused include: the Red River floods

in 1950 and 1997, with damage of \$125.5 million and \$500 million respectively (Rannie, 2014); Alberta flooding in 2005 and 2013, causing damage of \$519 million and \$6 billion respectively (Environment and Climate Change Canada, 2017); and the 1996 flooding events in Saguenay, Quebec, with damage of \$1.7 billion (Institute for Catastrophic Loss Reduction, 2010). Many studies have presented the high levels of vulnerability and low levels of preparedness among major cities across Canada, given the likely impact of climate change (Feltmate & Moudrak, 2021).

The combination of historical events and the risk of future events has promoted further application of flood mitigation and adaption strategies, which include both structural (infrastructure) and non-structural (policies and regulations) measures to reduce the risk of flooding. Structural measures employed in Canada include channel improvements, reservoirs, and dykes (Public Safety Canada, 2021). Channel improvements decrease flooding risks through altering the channel dimensions and characteristics, to either increase the maximum flow capacity or reduce the peak velocity of flow in the waterbody channel. Such measures have been implemented in Manitoba on the Red River, after the “Flood of the Century” in 1997, when the province underwent a floodway expansion to increase the capacity of the floodway from a 1-in-160 years event to a 1-in-700 years event (Manitoba Infrastructure, n.d.). A dam is an engineered structure that creates space for storing water to reduce and delay the peak flows of water in a stream or river that can cause flooding. Canada has 1157 operating large dams, with 22 of these having been built for the purpose of flood control and flood mitigation (Canadian Dam Association, 2019). Flood dykes are embankments or walls that act as barriers to prevent flooding of land behind the structure (Ministry of Water, Land and Air Protection Province of British Columbia, 2003). Dyke construction has occurred across Canada, with British Columbia having implemented 1,100 km of dikes to protect 160,000 hectares of land (Ministry of Forests, Lands and Natural Resource Operations, 2011).

While structural measures are commonly implemented across Canada, these measures have limitations in application. For one, structural measures require costly initial investments and consistent funding for maintenance. Dam and dyke structures

additionally are susceptible to overtopping failure that occurs when water spills over the structures. To further reduce the vulnerability of populations and infrastructure from flooding events, non-structural flood prevention measures have been implemented across Canada. Non-structural measures involve initiatives to keep people and infrastructure away from areas identified as vulnerable to flood hazards (Simonovic, 2002). Measures include land use regulation, floodplain mapping, flood forecasting, flood proofing, and emergency preparedness, among others. Although these measures are physically unable to prevent flooding of land, they can be implemented to restrict development in flood prone areas, to prepare human response to flooding, and to provide adequate warning and time for individuals to reduce their losses (Simonovic, 2002). One such activity to determine the extent of flooding and establish development restrictions is floodplain maps.

## **1.2 Floodplain Mapping**

Floodplain mapping is the process of deriving flood extent, flows, and elevation that result from a specified design flood event (NRCAN, 2018a). Floodplain maps are an essential tool for land use planning strategies, due to their ability to identify vulnerable areas that are susceptible to flooding events and for preventing any further development within such regions (De Moel et al., 2009). The number of floodplain maps is increasing across the world, with regions such as Europe introducing mandatory mapping requirements for vulnerable regions (European Parliament and the Council, 2007). While more recently floodplain maps have been produced through application of remote sensing data (Brivio et al., 2002; De Groeve, 2010), floodplain maps are generally produced through the use of statistical and numerical hydrologic and hydraulic modelling tools that are able to simulate flood conditions. Mapping approaches can be further categorised into three groups: Empirical Methods, Hydrodynamic Models, and Simplified Conceptual Models (Teng et al., 2017; Zheng et al., 2018). Floodplain Maps can also be applied with socioeconomic indicators to identify the population, infrastructure, and property exposed to the flood risks (Armenakis et al., 2017). While floodplain maps are a non-structural approach to management of floods, they can provide valuable details in determining locations that require further protective measures from flooding.

Canada first promoted the application of flood maps during the Flood Damage Reduction Program, which involved split funding from the federal and provincial governments to prepare floodplain maps (Bruce, 1976). Since the program's closure, the production of floodplain maps has varied across provinces, and some susceptible areas either lack updated flood maps or there are no flood maps at all. Floodplain mapping practices in Canada consider four different types of floodplain maps, namely Inundation Maps, Flood Hazard Maps, Flood Risk Maps, and Flood Awareness Maps (NRCAN, 2018a). Flood Inundation Maps present the inundation extent from historical and current flood events, and can help municipalities prepare for potential flooded extents. Flood Hazard Maps are produced following hydrologic and hydraulic models that simulate flood events using a regulatory design flood. Flood Risk Maps combine the flood hazard event with the probable socioeconomic impact following the flood event. Flood Awareness Maps present key information to the public regarding the impacts of historical flood events and the risks of future such instances.

As specified within the Flood Damage Reduction Program, floodplain maps were produced off a design flood event with a flood magnitude of a 100-year event or more (Bruce, 1976). Specifications allowed for variations in the design flood event from province to province, depending on the province's susceptibility to flooding. The technical specifications further allowed provinces to decide upon adopting a one-zone or two-zone flood hazard area. A one-zone flood hazard area involves one flood area where development restricts are constant, while the two-zone flood hazard area would include a floodway (high-risk area) and a flood fringe (low-risk area) where development policies depend on the risk of flooding (Bruce, 1976). As the susceptibility from flooding varies from province to province, floodplain mapping guidelines vary depending on the provincial level of risk from flooding. Since the introduction of the Program, elevated standards have been further adopted within certain provinces.

### **1.3 Large Region Floodplain Mapping**

Floodplain maps can be produced at a local scale in high resolution, which allow for more accurate flood hazard assessment for cities and communities (Merz et al., 2007).

While these local scale maps are highly effective, the cost and time involved in producing and maintaining them makes the process difficult for large countries such as Canada. Additionally, regions across the world lack sufficient hydrological information and high-resolution elevation data that can be effectively used to produce maps at such resolutions (Padi et al., 2011). The difficulties and restrictions in local scale mapping have prompted new methods for mapping regions on a larger scale—national, continental, and global scales.

The availability of global datasets and the improvements made in both computational power and numerical modelling have made large region floodplain maps more common in recent years (Dottori et al., 2016). Large region floodplain maps can provide valuable flood information across the globe and allow low-income countries to gain access to mapping previously unavailable due to high costs and lack of the required technology (Sampson et al., 2015). Additionally, the large region floodplain maps can cover entire countries and continents, cities and communities that currently do not have floodplain maps. They can provide flood information for neighbouring catchments and countries at the same time, a challenge that previously existed at the local scale (Hoch & Trigg, 2019; Jongmann et al., 2014). This further reduces both the cost and time needed to produce numerous local scale floodplain maps that can become quickly outdated because of land use changes and changes in flooding standards. Procedures and frameworks for the production of large region maps have been tested and applied on a global scale (Winsemius et al., 2013), continental scale (Wing et al., 2021), and national scale (Mohanty et al., 2020a).

Existing methods to analytically derive flood inundation extent can be grouped into three categories: empirical methods, hydrodynamic models, and simplified conceptual models (Teng et al., 2017). Due to their ability to accurately predict velocity, flood extent, and water level (Teng et al., 2017), hydrodynamical models have become popular in recent years. Hydrodynamic flood models utilise numerical and hydraulic equations to derive flood extent, volumes, and flows. Two frameworks for hydrodynamic models—FATHOM (Sampson et al., 2015) and CaMa-Flood (Mohanty & Simonovic,



2020a) have recently been applied for national scale floodplain maps for Canada. Spatial resolution varies between the two models, with the FATHOM model producing high resolutions of 90 m compared to the 1 km low resolution CaMa-Flood model.

#### **1.4 Scale Issues in Large Region Floodplain Mapping**

Advances in numerical models and computational speed have provided the ability to prepare continental or global scale floodplain maps with high resolutions of 90 m that can accurately identify flood extent at local scale (Rudari et al., 2015; Sampson et al., 2015). However, few such global scale maps are available, and a limiting issue for many large region maps remains the inability to produce floodplain maps at high spatial resolutions, due to the overall computational times being impractical (Zheng et al., 2018). The performance of large region floodplain maps at high spatial resolutions ( $< 100$  m) can require computational times up to three years to develop a floodplain map using a 1-year hydrograph for a global scale (Schumann et al., 2013a). This leads to sacrifices being made in the final spatial resolution, ultimately causing maps to consist of lower than ideal resolution (Wing et al., 2021). As a result, many large region floodplain maps continue to be produced at low resolutions of 1km x 1km (Dottori et al., 2016; Mohanty & Simonovic, 2020a; Winsemius et al., 2013). When maps offer only this degree of spatial resolution, they generally fail to effectively address risks on a local scale (Schumann et al., 2013b). These low resolutions are unable to follow satellite-derived river conditions of the stream mapped, when presented on to local scales.

An approach for improving the spatial resolution of maps is known as downscaling. Downscaling processes have been applied to improve the spatial resolution for climate (Gaur et al., 2018), remote sensing (Atkinson, 2013), and meteorological data (Mandal et al., 2016), enhancing the possibility of using the corresponding global datasets to address practical local-scale problems. Recently, there has been an increased focus on downscaling approaches adapted to low-resolution, large region floodplain maps (First Street Foundation, 2020; Schumann et al., 2013; Winsemius et al., 2013). Key techniques within the studied downscaling approaches use physical or statistical methods to improve the final spatial resolution. Physical downscaling techniques have involved

processes of imposing water surface elevations over predicted flooded pixels until the volume imposed within the high-resolution floodplain map is equal to that of the inputted low-resolution map (Winsemius et al., 2013). Statistical downscaling techniques have involved the application of bilinear resampling to reproject elevation data onto a higher resolution terrain model (First Street Foundation, 2020). While both downscaling approaches have the capability to improve spatial resolution, their feasibility for application within GFMs should be further evaluated.

By improving the resolution of large region maps through downscaling techniques, floodplain maps can be analysed for the purpose of local scale studies and implemented for land use planning and hazard mapping. Using higher-resolution floodplain maps with population and infrastructure datasets will additionally allow for higher accuracy in population and property exposure studies.

## **1.5 Research Objectives**

Given the lack of national floodplain mapping guidelines, there has been a marked absence of consistent standards for producing floodplain maps across the Canadian provinces and territories. Mapping standards vary according to the design flood event in place, the availability of floodplain maps, and the restrictions on development within the designated flood areas. Many mapping standards were first defined under the Flood Damage Reduction Program; however, depending on the province, some mapping standards have been changed since the establishment of the program. A recent push towards floodplain mapping has also been made by Natural Resources Canada (NRCAN), where they have promoted a joint approach to tackle floodplain mapping (NRCAN, 2018a). To better understand floodplain mapping practices in Canada, the first objective of this study is to:

- 1) Assess the current state of floodplain mapping across Canada

Mohanty and Simonovic (2020a) have recently developed a national floodplain mapping framework, which involved identifying six case studies within Canada. However, with the mapping having been completed at large scale, the spatial resolution

of 1km x 1km for the floodplain maps is too coarse to identify specific infrastructure and properties that are vulnerable to the flooded events. Therefore, to improve the final resolution of the floodplain maps, the second objective of the study is to:

- 2) Develop and evaluate an appropriate downscaling methodology for practical application with low-resolution floodplain maps

This thesis is structured as follows: Chapter 1, *Introduction*, has introduced the focus of the paper, establishing the key objectives that will guide the study. Chapter 2, *Floodplain Mapping in Canada*, discusses the history of the Flood Damage Reduction Program, in the extant floodplain map practices across the provinces and territories of Canada. This involves the completion of the first objective. Chapter 3, *Global Flood Models*, introduces Global Flood Models, going into details regarding their frameworks. The chapter contains a discussion on the framework developed by Mohanty and Simonovic (2020a) for application in Canada. Chapter 4, *Description of Downscaling Approaches*, establishes the relevant downscaling approaches adopted for floodplain mapping. Chapter 5, *Implementation of Downscaling for Global Flood Model*, presents the downscaling framework performed on two Canadian river basin case study floodplain maps. Chapter 6, *Results and Discussion*, presents the results of the downscaling framework as well as the test measurements performed to gauge the accuracy of the downscaling framework. This completes the second objective of the study. Chapter 7, *Conclusion*, summarises the findings of the study.

## **2. Floodplain Mapping in Canada**

### **2.1 Federal Flood Damage Reduction Program**

In April of 1975, the federal government announced the Flood Damage Reduction (FDR) Program in an effort to improve land-use planning. The Program was put in place as a result of the federal government completing a reassessment of specific flood related policies. With increasing disaster relief claims and a growing need for housing, the federal government came to the conclusion that more focused efforts were required to identify areas with flood risk. Prior to the Program, the Federal Government aided flood mitigation through two federal acts – The Canada Water Conservation Assistance Act and The Canada Water Act. The Canada Water Conservation Assistance Act was introduced in 1953 with the intention of providing provinces with federal financial assistance for the construction of flood management structures, while the Canada Water Act was introduced in 1970 with a focus on non-structural floodplain management strategies (Government of Canada, 1999).

The FDR Program identified that over 200 communities across Canada were consistently facing issues stemming from flooding (Bruce, 1976). This resulted in the Program focusing on the preparation of floodplain maps for the flood prone communities, with secondary efforts in flood forecasting and warning services. Under the FDR Program, the floodplain maps would adopt hydrologic and hydraulic analysis techniques to delineate the flood risk areas and derive flood depths and flows (Bruce, 1976). These engineering maps would provide the basis for zoning regulations and land use planning policies, avoiding the construction of further developments in areas of high flood risk. Key technical specifications were introduced, which focused on flood risk areas, consisting of the design flood event extent and either a one-zone or a two-zone concept. A one-zone concept involves the flood hazard area consisting of one area that has been derived from the design flood event. Management and development policies throughout the flood hazard area are constant. A two-zone concept involves the flood hazard area consisting of two areas, namely a floodway and a flood fringe. While the specifications for the determination of the floodway and flood fringe vary across provinces, the floodway involves the high flood risk zone, where the development of infrastructure is

restricted, whereas the flood fringe involves the low flood risk zone, where the development of infrastructure is permitted under flood proofing guidelines. Specifications for the design flood event included the magnitude of the event, consisting of a 100-year flood event or greater, and left each province responsible for the decision. Provinces could also decide whether they wanted to adopt a one-zone or a two-zone flood area policy, where a two-zone policy would establish different flood regulations for flood waters having either shallow or deep flood depths. The costs of the Program were to be split evenly between the federal and provincial governments, with initial cost projections reaching \$20 million for the first 5 years of the Program (Bruce, 1976). With all provinces barring Prince Edward Island and the Yukon Territory signing agreements, the Program began with six pilot projects for the communities of Fredericton, Moose Jaw, Carman, Oshawa, Sault Ste. Marie, and Montreal.

An evaluation of the FDR program was completed in 1990, where the federal government considered the Program to have had an exceptional impact in preventing further development in flood prone areas, especially in urban flood risk areas (Edgar Watt, 1995). Further policy and flood map maintenance were discussed as being vital, otherwise flood damage and the need for disaster assistance would arise again in the future.

Once the mapping was considered to have attained completion, the FDR Program came to an end in 1998. Following the closure, provincial governments have become responsible for the production of further floodplain mapping and maintenance of existing floodplain mapping. In total, the program resulted in the mapping of over 320 flood risk areas, covering more than 900 communities across Canada. Overall funding from the Program came to an end in the early 2000s (Government of Canada, 2010).

## **2.2 Current Status of Floodplain mapping in Canada**

Following completion of the FDR Program, each province and territory became responsible for ensuring that floodplain mapping was maintained and continued for land use planning. As a result of increasing disaster risks and costs, the Federal Government of

Canada announced the introduction of the National Disaster Mitigation Program (NDMP) in 2014 (Public Safety Canada, 2021). The programs purpose was to combat rising residential insurances from flooding and focus investments on regions experiencing significant and recurring flooding (Public Safety Canada, 2021). In 2020, the Federal Government announced the renewal of the NDMP. Due to a lack of standards from the federal level for flood map guidelines, each province and territory has a different level of flood regulations and flood map collections.

### ***2.2.1 British Columbia***

The province of British Columbia (BC) has faced continued and severe flooding in its history, with recorded flooding events dating back to 1894. Annual freshet flooding events occur as a result of melting snowpacks' combining with precipitation events during the spring. With split funding from the FDR Program, BC established the Floodplain Development Control Program in 1975. The program ran from 1987 to 2003, and directly contributed to an increase in the production of floodplain maps for all flood prone regions and communities across BC. Following the completion of the provincial program, a limited number of regions have seen updates and maintenance within regional floodplain maps. An additional 31% of communities in the province remain without any form of floodplain maps (Parsons & BCREA, 2015).

Currently, BC is implementing a one-zone flood design, with the design flood event occupying a return period of 200 years (Ministry of Water, Land and Air Protection Province of British Columbia, 2004). Freeboard levels have been added on to the design elevations, where a height of 0.3 m above the maximum instantaneous design flood level or 0.6m above the mean daily design flood level, whichever is greater, is reckoned (Ministry of Water, Land and Air Protection Province of British Columbia, 2004). The maximum instantaneous design flood level is the peak flood level of the 200-year design flood at any point in time, whereas the mean daily design flood level is the flood level above the 200-year design flood's average daily flow (Ministry of Water, Land and Air Protection Province of British Columbia, 2003). Development within the one-zone flood

area is limited and requires adequate flood proofing measures. Additional measures for a 20-year return period flood event have been adopted through the Health Act for the use of septic systems (Professional Engineers and Geoscientists of BC, 2017).

iMapBC is an online interactive map software that presents map layers ranging from agricultural land reserve planning to land use planning. Included within the layer options is the historical floodplain layer from historical map drawings produced under the Flood Development Control Program. The map resource has been made freely available to the public and can be accessed through the following URL:

<https://maps.gov.bc.ca/ess/hm/imap4m/>. The mapping software uses a street map as the base map and provincially produced layers can be imported by selecting the desired map layer. Besides the interactive map service, historical floodplain maps have been uploaded to the province's governmental website for communities with high risk of flooding. An example of the historical floodplain map drawing can be seen in Figure 1.

In recent years, the Fraser Basin Council have initiated efforts for better flood management strategies and planning through the production of floodplain maps for the Lower Fraser River Basin. The maps include four different freshet flood events with Annual Exceedance Probabilities (AEP) of 2%, 1%, 0.5%, and 0.2%. Included within the mapping collection is the flood map for the 1894 flood event, which is the current flood event on record for the province (Fraser River Council, n.d.). Climate change impacts reflected in rising sea levels have been included within selected floodplain maps. The first scenario involves a 0.5m sea level rise estimated for 2050, while the second scenario involves a 1m sea level rise estimated for 2100. Figure 2 presents an engineered floodplain map presenting the flooded extent under a 1% AEP with the 2100 climate change scenario.



Figure 1: iMapBC application presenting the floodplain maps for the Chilliwack and Vedder rivers (Government of British Columbia, n.d.)

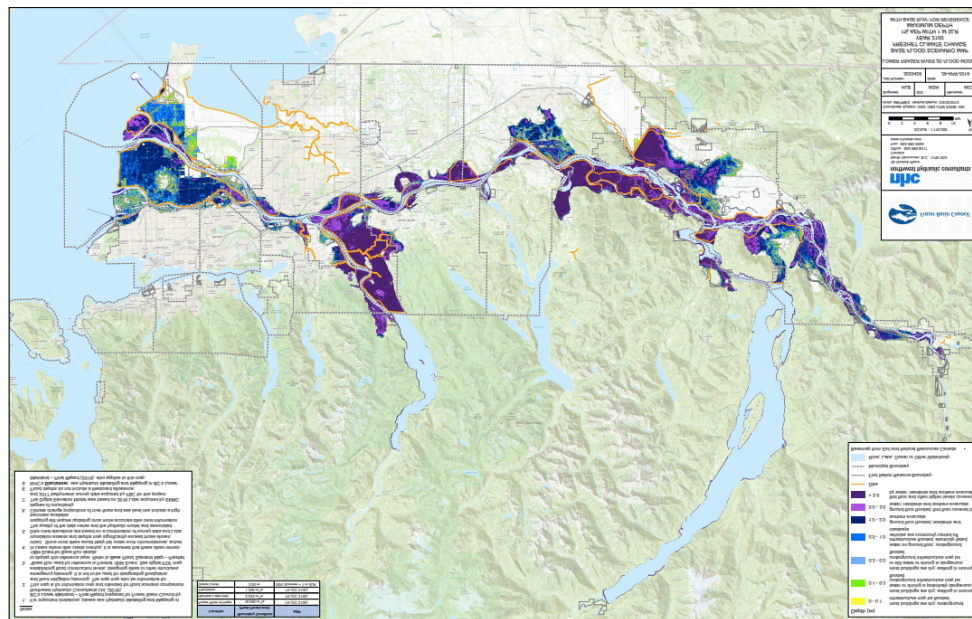


Figure 2: Fraser River Council 100-year design flood for 2100 climate change scenario with 1m sea level rise (Fraser River Council, 2019)



### **2.2.2 Alberta**

The province of Alberta has witnessed two major flooding events in the past 20 years, with the second event in the spring of 2013 being the costliest insured natural catastrophe in Canadian history at the time of occurrence (ICLR, 2013). The final economic damage as a result of the 2013 event is estimated to have reached \$6 billion (Environment and Climate Change Canada, 2017). The result of snowpack melting from rainfall during the spring has caused spring flooding to become an annual cause of concern.

Floodplain mapping across Alberta began in the 1970s when the federal government announced the FDR Program for a more coordinated national approach towards flooding. The funding from the program allowed Alberta to establish the Canada–Alberta Flood Damage Reduction Program in 1989 (Government of Alberta, 2020). The provincial program was set with the duration of 10 years, with the purpose of production of floodplain maps under the cost sharing arrangement. Since the program's conclusion, Alberta has continued to produce floodplain maps for flood prone communities.

Mapping standards for Alberta include both a design flood event of a 100-year return period and a two-zone flood hazard area that includes a floodway and flood fringe (Government of Alberta, n.d.). The floodway occupies the portion of the flood hazard area where water flows are identified as being the deepest, fastest, and most destructive. The area must meet one of the following requirements to be considered a floodway: encroachment conditions where there is a maximum rise of 0.3 m in the water level due to river flow, where there is a flood depth of 1 m, or where there is a velocity of 1 m/s. Any development within the floodway is discouraged. The flood fringe is defined as the flood hazard area outside the floodway for the 100-year return period, where water levels are shallower, with lower flow levels. The velocity and flood depth are less than 1 m/s and 1m, respectively (Alberta Environment Water Management Operations River Forecast Section, 2011). Development within the flood fringe must include flood proofing to account for the design flood level conditions. In addition to the design flood

event, Alberta employs a 1:500-year return period for the protection of lifeline facilities critical to the maintenance of public order and a 1:1000-year return period for the restricted development of vital lifeline facilities (Government of Alberta, 2017).

Similar to BC, Alberta currently uses an online interactive mapping application that presents the floodplain maps produced under the FDR Program. The maps present both the floodway and flood fringe for the design flood of 100-year return period. Flood elevations for selected cross-sections are included within the mapping application to improve the general public's understanding of the maps. All maps and cross-sections have been made freely available to the public and can be accessed through the following URL: <https://floods.alberta.ca/>. The mapping service is simple to use as it only requires the user to zoom in on any desired flood risk area they want to observe. An example of the flood mapping service is visualised in Figure 3. Future projects involving flood assessment are set to begin, with the aim to address regions of Alberta currently having inadequate or no floodplain mapping.

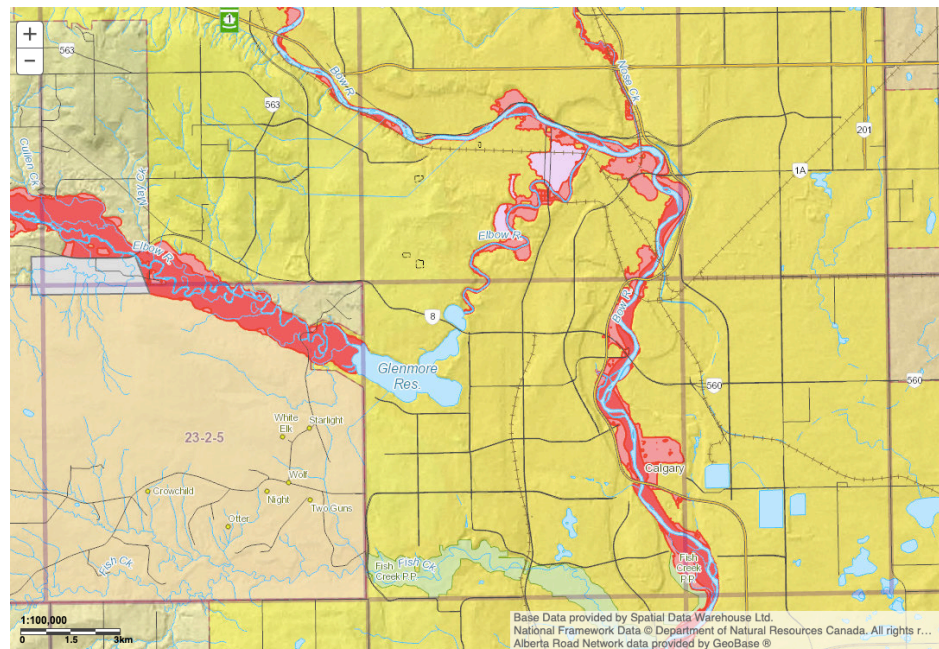


Figure 3: Flood Hazard Map Application Alberta presenting the derived floodway (dark red) and flood fringe (light red) for the flood hazard area (Government of Alberta, 2019)

### **2.2.3 Saskatchewan**

Recent spring flooding events have forced the province of Saskatchewan to revisit the need for maintained floodplain maps. One such event includes the 2011 spring flooding which occurred from lengthy rainfall and the melting of a snowpack along the Rocky Mountains (Water Security Agency Saskatchewan, 2013). The event led to flows ranging from a minimum 5-year return period and reaching up to the level of a 500-year return period flood event in the Regina area (Water Security Agency Saskatchewan, 2013).

Design flood regulations for Saskatchewan consider a 500-year return period, which are the most rigorous measures adopted by any Canadian province (Government of Saskatchewan, 2012). The design flood event employs a two-zone flood hazard area. The standards for definition of the floodway include the area of land inundated with flood velocities equalling or exceeding 1 m/s or water depths equal to or exceeding 1 m. The remaining flood hazard area is defined as the flood fringe. Measures for the floodway prohibit any new development, while new development within the flood fringe is restricted to situations where flood proofing is completed up to an elevation of 0.5m above the design flood elevation (Government of Saskatchewan, 2012).

In the past, Saskatchewan has made use of Geo Sask, an interactive online application, to allow public access to flood map products. The application was shut down in 2016, along with its URL, and the floodplain maps have not been made freely available to the public since. The Saskatchewan Water Security Agency is currently in the process of implementing a new floodplain mapping project within the Natural Disaster Mitigation Program. The project has identified 20 high risk communities in need of increased flood management, with a proposed goal of the production of floodplain maps for each community. Melfort, Moose Jaw, Regina, Saskatoon, Weyburn, and Yorkton are included within the 20 high risk communities, alongside several other towns and villages (Government of Saskatchewan, 2019). The project has an expected completion date of 2030 and the products and findings of the project will be made available to the public.

#### **2.2.4 Manitoba**

The majority of floodplain maps produced for the province of Manitoba occurred during the FDR Program that existed federally until the 1990s. Since conclusion of the program, Manitoba has undertaken no further updates or maintenance of the historical map collection (National Research Council Canada, 2017). The standards implemented within the mapping process involve design flood event with a return period of 100 years and a two-zone flood hazard area. The two-zone flood hazard area is composed of a floodway, which occupies an area of flood depth greater than 1m, and the flood fringe, which accounts for the remaining inundated area from the design flood (Babaei & National Research Council Canada, 2017). Designated flood areas have been defined in select locations across Manitoba. Within these areas, flood protection levels must be taken into account for the development of infrastructure.

With recent major flooding events causing damage in Manitoba in 2009 and 2011, the province has been forced to take an increasingly conservative approach towards flooding. This involves the change to a design flood of 200-year return period, as the design flood water elevations are to account for recent flooding events (Babaei & National Research Council Canada, 2017). Included within the new design flood standards are methods to reckon the climate change impacts on flooding, specifically in relation to precipitation changes. Potential methods include the addition of new meteorological stations and continual development of updated IDF curves. At the current moment, no new updated guidelines for return period or climate change have been used in floodplain mapping; however, Manitoba has recently announced a new project that would perform a floodplain mapping for the Lower Assiniboine River, Souris River, and Whitemud River (Babaei & National Research Council Canada, 2017).

Additional floodplain mitigation strategies in Manitoba were completed in 2005 to counteract heavy and frequent flooding along the Red River. The Canadian and Manitoban governments made a collaborative investment of \$628 million for the purpose of expanding the Red River Floodway flow capacity. The project increased the flow capacity along the floodway from 1,700 m<sup>3</sup>/s to 3,963 m<sup>3</sup>/s, allowing the floodway to

hold a design flood event with 700-year return period compared to the original capacity of 160 years (Manitoba Infrastructure, n.d.).

Manitoba Infrastructure is currently in sole possession of the floodplain maps produced under the FDR Program. Due to the fear of misuse and misinterpretation by the general public, the maps have not been made available to the public online (Babaei & National Research Council Canada, 2017). While new projects have been announced, it remains unclear whether the floodplain maps will be published for the local population.

### **2.2.5 Ontario**

In contrast to other provinces, Ontario has developed a unique scenario for flood management and floodplain mapping responsibility. The province has been divided into 36 conservation authorities based on regional watersheds, where the conservation authorities have the sole responsibility for their outlined region. Conservation authorities have produced floodplain maps for a total of 22,000 km of flood prone areas, accounting for 90% of all rivers and creeks across Ontario (Conservation Ontario, n.d.).

The design flood event standard is specified as the flooding hazard limit and is considered to be the greater of:

- I. The flood resulting from a rainfall actually experienced during a major storm such as the Hurricane Hazel storm (1954) or the Timmins storm (1961), transposed over a specific watershed and combined with the local conditions, where evidence suggests that the storm event could have potentially occurred over watersheds in the general area;
- II. The 100-year flood; or
- III. A flood greater than i) or ii) which was actually experienced on a particular watershed or portion thereof, for example as a result of ice jams and which has been approved as the standard for that specific area by the Minister of Natural resource (Ontario Ministry of Natural Resources, 2002).

A complete breakdown of the design flood standards implemented within each Conservation Authority in Ontario is provided in Appendix A.

As a result of conservation authorities having sole responsibility for practices, flooding standards and mapping availability range across the various watersheds. Guidelines for conservation authorities allow either the one-zone or two-zone concept to be implemented within the floodplain. The two-zone concept identifies the floodway as the inner area of the floodplain, where the flood depth is greater than 1m and/or flow velocities are above 1m/s (Ontario Ministry of Natural Resources, 2002). The flood fringe is considered to be the remaining outside area of the floodplain. Development within the floodway is prohibited, while development within the flood fringe must abide by flood proofing standards.

Availability of floodplain maps for the public is another varying aspect of the conservation authority system. The availability of floodplain maps ranges from interactive web services, as set up by the Toronto and Region Conservation Authority (TRCA), to flood map drawings of the general regulated area, such as by the Mississippi Valley Conservation Authority. The conservation authorities that have implemented online mapping software are mentioned, with their available URLs, below:

- The Essex County Conservation Authority
  - ([http://gisweb.countyofessex.ca/htmlerca2112/Index.html?configBase=http://gisweb.countyofessex.ca/Geocortex/Essentials/ERCA/REST/sites/ERCA\\_Public/viewers/htmlpublic/virtualdirectory/Resources/Config/Default](http://gisweb.countyofessex.ca/htmlerca2112/Index.html?configBase=http://gisweb.countyofessex.ca/Geocortex/Essentials/ERCA/REST/sites/ERCA_Public/viewers/htmlpublic/virtualdirectory/Resources/Config/Default))
- Grand River Conservation Authority
  - <https://maps.grandriver.ca/web-gis/public/?theme=General&bbox=530871,4783341,658785,4882509>
- Upper Thames River Conservation Authority
  - <https://maps.thamesriver.on.ca/gvh/?viewer=regulations>
- Rideau Valley Conservation Authority
  - <https://gis.rvca.ca/html5/?viewer=rvcageoportal>
- Toronto and Region Conservation Authority
  - <https://arcgis01.trca.on.ca/floodplain/>
- Central Lake Ontario Conservation Authority

- <https://camaps.maps.arcgis.com/apps/webappviewer/index.html?id=6bff662ccd214b619928ec2aa589080c>

The interactive maps are simple to use and involve zooming into a desired flood risk area to observe. An example of the interactive online floodplain map for the Toronto and Region Conservation Authority is visualised in Figure 4. Floodplain map drawings are produced for gridded zones within a flood risk area. They can be accessed by visiting the desired conservation authority website and selecting the zone that occupies the flood risk region the user wishes to observe. An example of the Mississippi Valley Conservation Authority floodplain drawing can be seen in Figure 5.



Figure 4: TRCA Interactive Floodplain Map (<https://trca.ca/conservation/flood-risk-management/flood-plain-map-viewer/>)



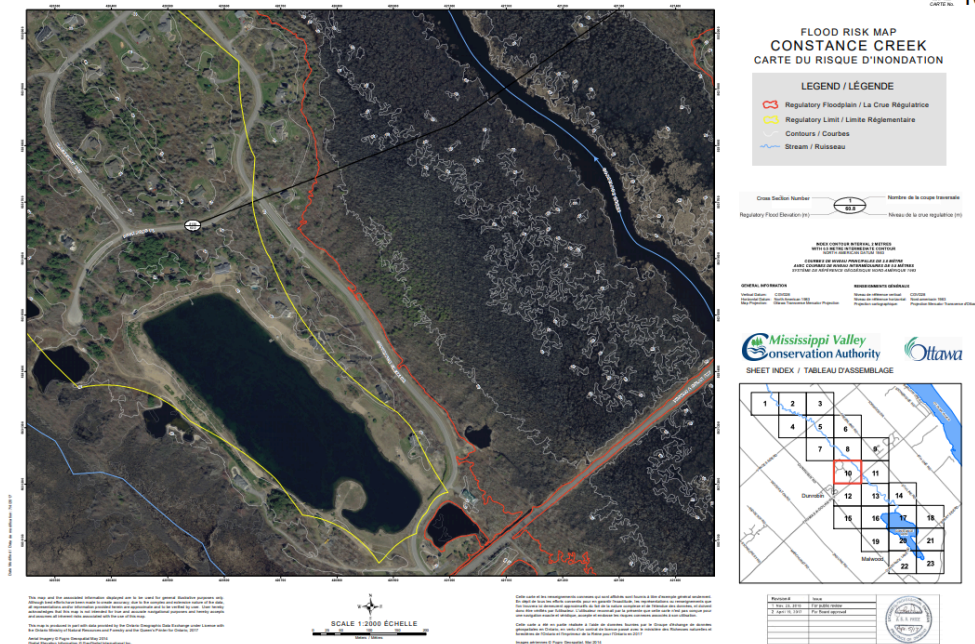


Figure 5: Floodplain map presenting the regulatory floodplain and limit for Constance Creek in the Mississippi Valley Conservation Authority (<https://mvc.on.ca/development-permits/flood-prone-areas-and-map/constance-creek/>)

### 2.2.6 Quebec

Published floodplain mapping guidelines for the province of Quebec were presented through the Protection Policy for Lakeshores, Riverbanks, Littoral Zones, and Floodplains Environment Quality Act (Gouvernement du Québec, 2005). Quebec utilises a two-zone flood hazard area composed of a high velocity zone and a low velocity zone. The high velocity zone is defined as the area occupying the flooded volume of water from a design flood event with 20-year return period (Gouvernement du Québec, 2005). The low velocity zone is then defined as the area outside the high velocity zone occupying the flooded volume of water from a design flood event with a 100-year return period (Gouvernement du Québec, 2005). Development within the high velocity zone is restricted and development in the low velocity zone requires flood proofing methods to avoid potential damage. Flood proofing measures include no ground flood lower than the level of the 100-year flood elevation, no opening lower than the 100-year flood elevation, and drains that have a non-return backup valve (Gouvernement du Québec, 2005).



The combination of spring snowmelt and intense precipitation events led to heavy flooding in 2017 and 2019. Specifically in 2019, 9,800 homes were flooded and a total of \$127 million worth of damage was reported. As a result, Quebec initiated a draft for the purpose of a new act that would further strengthen floodplain management (Gouvernement du Québec, 2019). The draft was then published on the 15<sup>th</sup> of July 2019, and within the draft a freeze was placed on all construction and repairs to infrastructure that were located within the “Zone d’intervention spéciale”. The “Zone d’intervention spéciale” is defined as the greater of either the flooded area from the flood fringe (20-year flood elevation level) or the flooded area from the 2017 and 2019 events (Gouvernement du Québec, 2005).

Following conclusion of the mapping from the “Zone d’intervention spéciale”, Quebec published the floodplain maps on an online web application that was made available to the public. Included within the flood map is a GIS ESRI satellite based map. The mapping service can be accessed through the following URL: <https://www.cehq.gouv.qc.ca/zones-inond/ZIS-20190715/index.html>. The online tool covers 776 municipalities. An example of the “Zone d’intervention spéciale” can be seen in Figure 6.

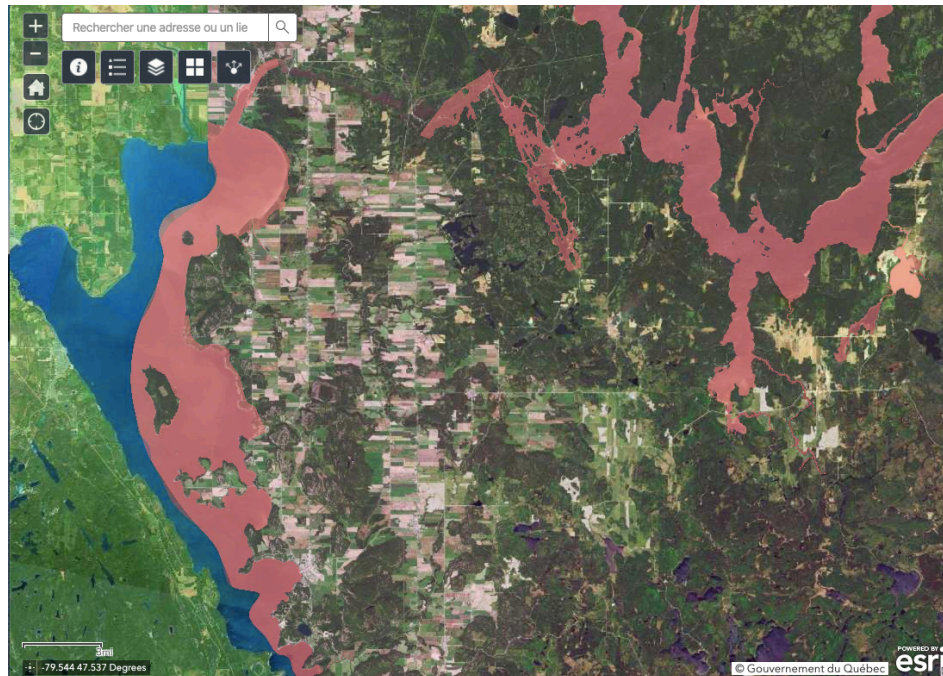


Figure 6: “Zone d’intervention spéciale” presents the delineated flood zone that resulted from the spring floods of 2017 and 2019 (Gouvernement du Québec, 2019)

### 2.2.7 *New Brunswick*

The province of New Brunswick focused their production of floodplain maps for inland flood hazard areas from the beginning of the FDR Program in 1976 until 2000. Recently, the province has switched focus to the production of coastal flood hazard maps due to concerns regarding the rising sea level. This has led to the historical inland floodplain maps being neglected and becoming outdated with reference to the new technology that has become available.

Flood mitigation practices in New Brunswick involve a two-zone flood hazard area composed of the floodway and flood risk area. The floodway is defined as the inundated area for a design flood with a 20-year return period. Any further development is restricted. The flood risk area is defined as the area of flooded water from a design flood with a 100-year return period outside the floodway region (Government of New Brunswick, n.d.). Any further development in the flood risk area is required to not reduce the flood water storage capacity of the area. The Government of New Brunswick utilises

an online application to allow the public access to the floodplain maps (<https://geonb.snb.ca/geonb/>) and further flood management policies. The online tool projects the areas expected to be inundated in both the floodway and the flood risk area, besides including two historic flood events from the years of 1973 and 2008. Further historical flood map drawings are available on the Government of New Brunswick's website (<https://elg-egl.maps.arcgis.com/apps/PanelsLegend/index.html?appid=30b97c1830b84fbd8e581a6d05243bb9>).

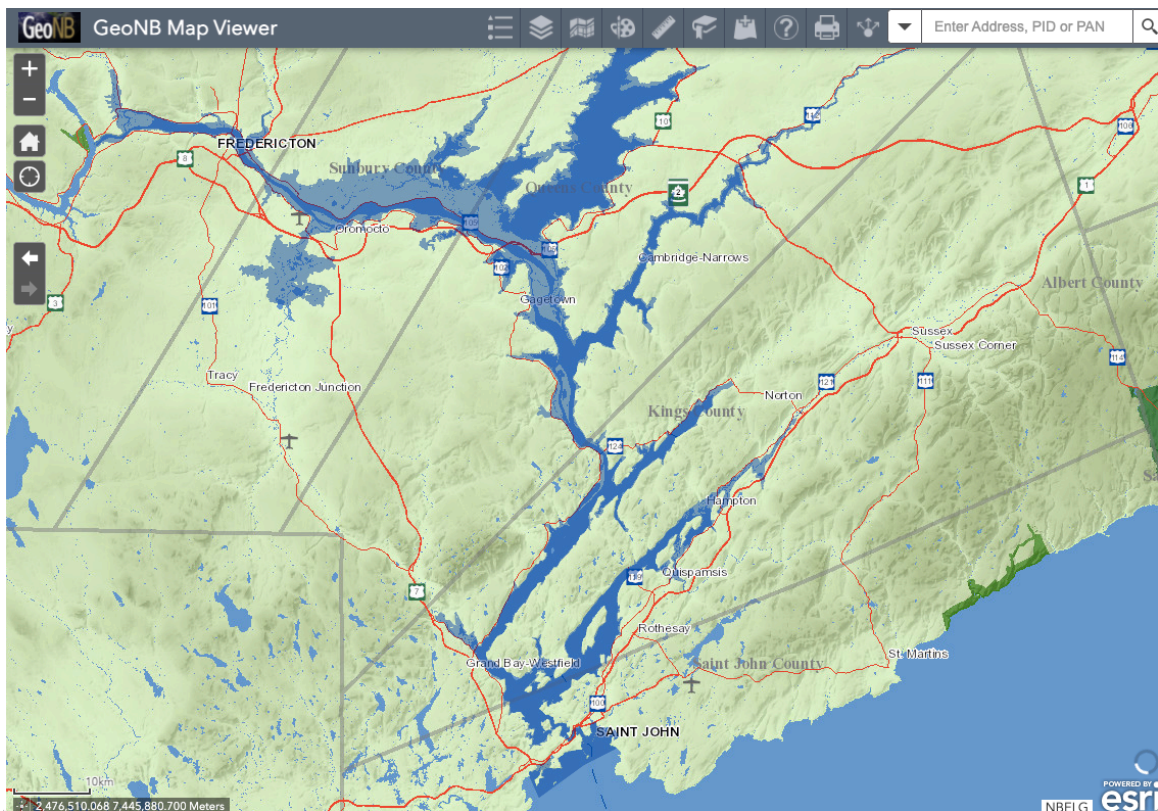


Figure 7: GeoNB interactive online floodplain map that presents the 2018 Lower Saint John River floods. The blue outline represents the extent of the flood event (GeoNB, 2018)

A new Inland Flood Hazard Mapping Project has been announced and is expected to start by the late 2020s. The project is in collaboration with Public Safety Canada and the main goals of the project involve updating and maintaining the historic maps, while also expanding to further areas across the province (Boisvert, 2020; Government of New



Brunswick, 2020). There are no further updates from the New Brunswick Government on the progress of the project.

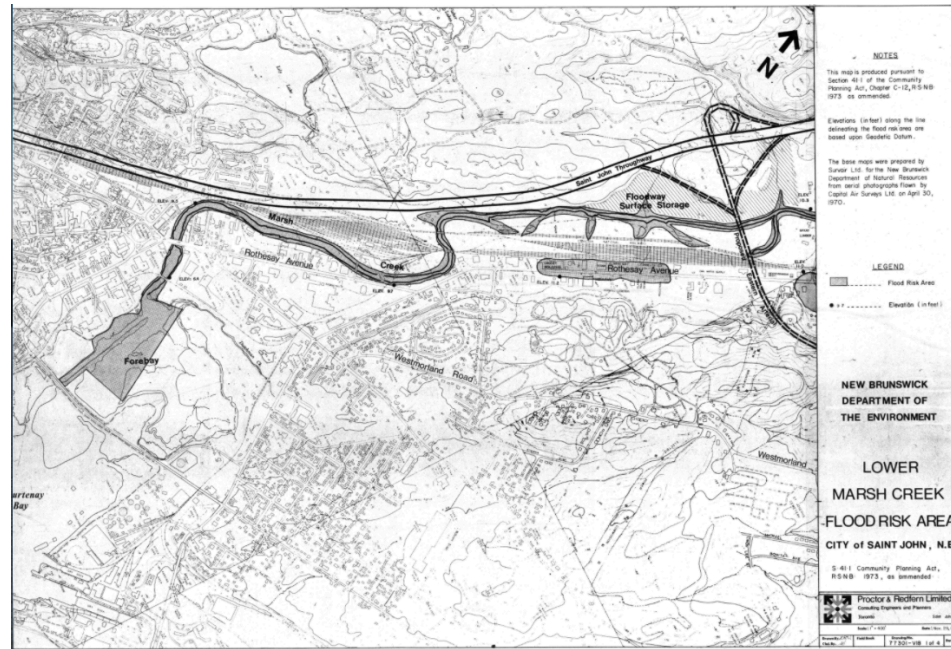


Figure 8: Historical floodplain map drawing for the Lower Marsh Creek flood risk area (Government of New Brunswick, 1979)

### 2.2.8 Newfoundland and Labrador

Floodplain mapping under the FDR Program lasted in the province of Newfoundland and Labrador from 1981 to 1993. Within this time frame, the province was able to identify 37 communities where flood management and floodplain mapping were required to reduce the communities' vulnerability. The floodplain mapping standards included a two-zone flood hazard area policy composed of a floodway and floodway fringe (Government of Newfoundland and Labrador, 2014).

In 2009, the province established a new three-zone flood hazard area that would become the new standard. The three zones include the traditional floodway and flood fringe, as well as a new climate change zone. The floodway is defined as the flooded area of a design flood with a 20-year return period, while the floodway fringe is the flooded

area of a design flood with a 100-year return period and outside the floodway (Government of Newfoundland and Labrador, 2014). The climate change zone is considered to be an extension of the floodway fringe, with the goal of presenting the impact climate change will have on the flood hazard area. Impacts involved in this zone include using a 2050 maximum IDF relationship as a result of climate change (Government of Newfoundland and Labrador, 2014). Development related to temporary alterations, non-structural uses, structures related to use of water resources, and hydraulic structures are permitted. However, the majority of development categories require compliance with flood proofing conditions. Residential areas are not permitted within the floodway, while institutional development is not permitted within any zone.

Recent studies that include the three-zone flood hazard area have been published under the Flood Risk Mapping Studies section of the provincial government's website. The maps have been made freely available to the public and discuss the specific climate scenarios used. In addition to the floodplain maps, reports discussing hydrotechnical studies, mapping projects, and other mapping studies in relation to flood risk management are included. All maps and studies can be found and selected through <https://www.gov.nl.ca/ecc/waterres/flooding/frm/>. Figure 9 presents the flood extent delineated from a regional study in Corner Brook.

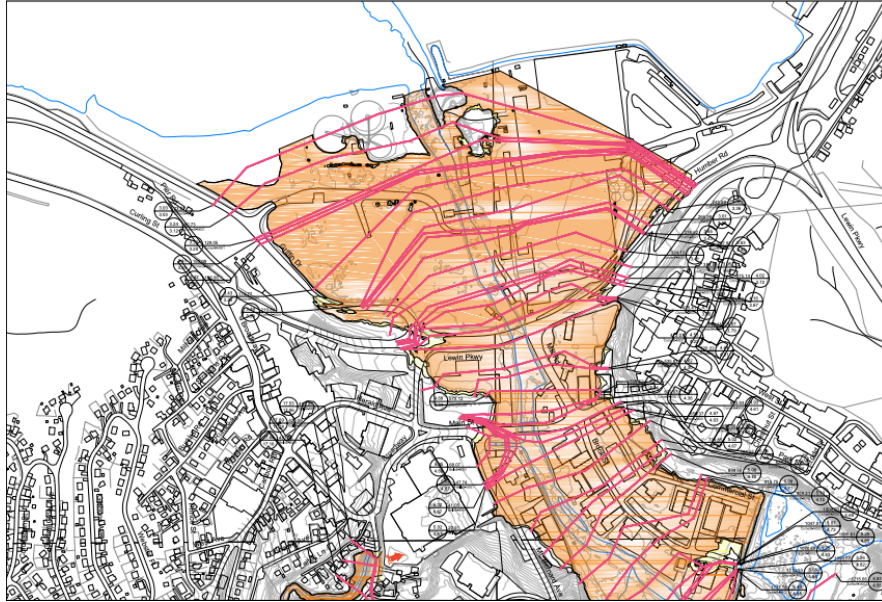


Figure 9: 1:20 and 1:100 Annual Exceedance Probability climate change flood lines using the 2050 maximum IDF relationship for Corner Brook (Government of Newfoundland and Labrador, 2013)

### 2.2.9 *Nova Scotia*

The province of Nova Scotia focused their efforts from funding under the FDR Program for the communities of East River, Little Sackville River, Sackville River, Salmon and North Rivers, and West and Rights Rivers and Brierly Brook (Government of Nova Scotia, 2013). The flood management guidelines for the flood map series included a two-zone flood risk area composed of a floodway and flood fringe. The floodway is defined as the flooded area for a design flood of 20-year return period. The flood fringe is defined as the area that coincides with both the area of flooded water for a design flood of 100-year return period and the area outside the floodway (Government of Nova Scotia, 2013). Development within the floodway is restricted only to the construction of roads, open spaces, parking lots, and temporary uses of the land. Infrastructure with flood proofing measures is permitted within the flood fringe; however, development of residential institutions or any use associated with warehousing or production of hazardous materials is restricted.

Considering the need for updated and easily accessible floodplain maps, CBCL Limited started a new project for floodplain mapping in 2017 for the City of Halifax. The goal of the project was to present a new set of floodplain maps for the flood hazard area contained in the Sackville and Little Sackville Rivers (Halifax Regional Municipality, 2019). The maps use the provincial standards for municipal planning regulations, but take into account appropriate updates for river channel changes and development of land, as well as technology updates.

Historical floodplain maps can be accessed by contacting the Geomatics Nova Scotia centre ([geoinfo@novascotia.ca](mailto:geoinfo@novascotia.ca)). In addition, the City of Halifax has constructed an online interactive web tool (<https://www.arcgis.com/apps/webappviewer/index.html?id=54adf80df5d94459a8ea08554997fa07>) that displays the mapped floodway and flood fringe within the flood hazard area. The tool utilises a satellite-based map to help identify the flood prone regions. Accessibility is made simple through users only being required to drag the map to the flood risk region they want to observe. An example of the floodplain map produced for the Sackville region is presented in Figure 10.

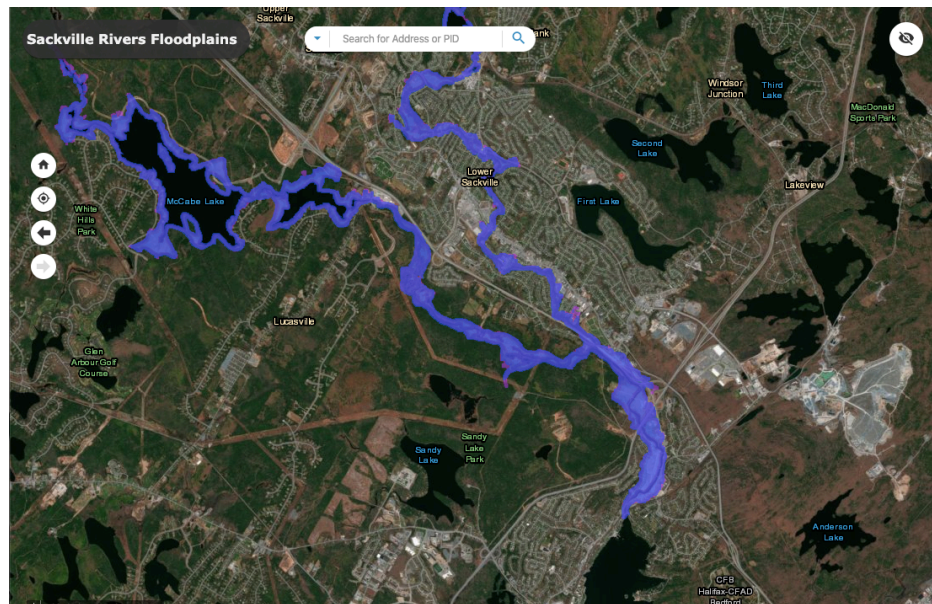


Figure 10: City of Halifax Floodplain Map that presents the floodway (blue) and flood fringe (purple) for the Sackville Region (City of Halifax, 2017)

### ***2.2.10 Prince Edward Island***

As mentioned in Section 2.1, the province of Prince Edward Island (PEI) did not participate in the national FDR Program and instead focused its efforts on coastal flooding and erosion. As such, PEI employed limited inland flood management guidelines (Bruce, 1976). One policy in relation to flood management requires all watercourses to include a buffer zone with an area of 15 m where certain activities are to be restricted (Prince Edward Island Department of Communities, Land and Environment, 2016). The activities are as follows:

- Drain, pump, dredge, excavate or remove soil, water, mud, sand, gravel, stones, rubbish, rocks, aggregate or material or objects of any kind;
- Dump or infill, or deposit soil, water, mud, sand, gravel, stones, rubbish, rocks, aggregate or material or objects of any kind;
- Construct or place, repair or replace, demolish or remove, buildings or structures or obstructions of any kind; and
- Operation of heavy equipment on the sediment bed, beach or bank of a watercourse; exception involves motor vehicle on a beach for activities to do with legal harvesting of a fishery resource or the legal removal of beach material. (Prince Edward Island Department of Communities, Land and Environment, 2016)

The Atlantic Climate Adaptation Solutions Association (ACASA) project is a partnership among the Atlantic Maritime provinces. They have undergone several projects for the Atlantic coast that include inland floodplain mapping, coastal floodplain mapping, erosion assessments, and more. ACASA identified four flood prone regions in PEI and were in need of further floodplain maps to better flood management. The communities included Mount Stewart, North Rustico, Souris and Souris West, and Victoria. The project resulted in floodplain maps that consisted of a combination of scenarios, including sea level projections for 2050 and 2100, and storm surge return periods of 10, 25, 50, and 100 years (ACASA, 2012). All floodplain maps have been made available through their online website to better identify key areas at risk (<https://atlanticadaptation.ca/en/islandora/object/acasa%3A627>). The website lists all floodplain maps with their incorporated sea level rise scenario, and these can simply be



selected by the user and viewed. Figure 11 presents the 2050 floodplain hazard map for Mount Stewart.

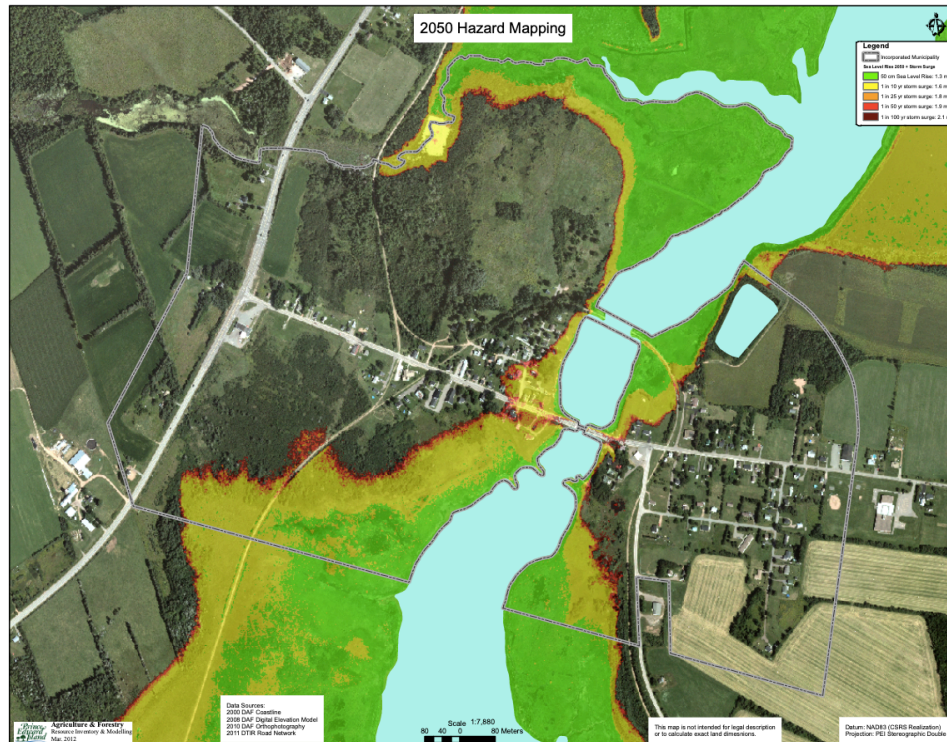


Figure 11: ACASA produced 2050 hazard floodplain map for the community of Mount Stewart. The map presents the extent of flooding resulting from conditions involving a 50 cm sea level rise (green), and 1 in 10-year (yellow), 1 in 25-year (orange), 1 in 50-year (red) and 1 in 100-year (brown) storm surge (ACASA, 2012).

### 2.2.11 Northwest Territories

The Northwest Territories in collaboration with the Administration of the Territorial Lands Act System (ATLAS) completed a project involving the production of floodplain maps that would be presented using an online interactive tool. Flood guidelines used include a design flood with a 100-year return period and a two-zone flood hazard area with a floodway and flood fringe (ATLAS, 2017). The floodway and flood fringe follow the guidelines from the FDR Program, where the floodway is defined as the land inundated by a flood depth greater than 1 m and the flood fringe is the remaining outside inundated area. The online tool can be accessed through [https://www.maps.geomatics.gov.nt.ca/HTML5Viewer\\_Prod/index.html?viewer=ATLAS](https://www.maps.geomatics.gov.nt.ca/HTML5Viewer_Prod/index.html?viewer=ATLAS). Similar to the

other online tools, this map presents various layers, which include the floodway and flood fringe, that can be selected and presented over the base map. Mapping was limited to communities in need of managing current flood hazards, and as a result the floodplain mapping is not continuous through the territory. Figure 12 is an example of the floodplain map showing the flooded extent for the Fort Simpson region.

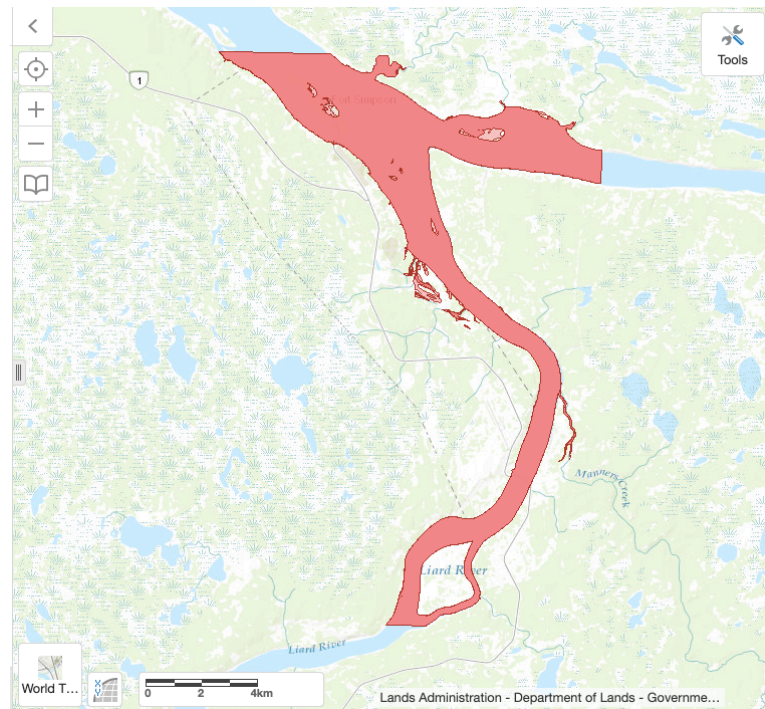


Figure 12: ATLAS Interactive Floodplain Map presenting the flood risk area for Fort Simpson (ATLAS, 2017)

### ***2.2.12 Nunavut***

As Nunavut was only designated as a Canadian Territory at the conclusion of the FDR Project, the Territory has no available floodplain maps to identify flood hazards. Climate change implications have caused Nunavut to develop coastal mapping assessments for risk adaptation.

### **2.2.13 Yukon**

The Yukon has established only limited flood management policies during its history, and as a result the territory lacks regional floodplain maps. With fears of future flooding damage, the Government of Yukon and Yukon Water have established a new Flood Risk Mapping Project. Aims for the project include utilising new LiDAR surveys for 13 local communities, to be completed between 2014 and 2015 (Yukon Water, n.d.). However, the project is yet to be completed and Yukon Water have provided no further updates on the project.

## **2.3 Federal Flood mapping Guideline Series**

Initiating efforts to establish a unified national approach to floodplain mapping, in 2018 Natural Resources Canada (NRCAN) issued a Federal Flood Mapping Guideline series (NRCAN, 2018a). The series includes nine documents (two documents still to be completed) with varying technical concepts for provincial and territorial governments to focus on to improve floodplain mapping across Canada. Within the guideline series, NRCAN has established a framework for performing floodplain mapping and flood risk assessments. Figure 13 presents the floodplain mapping framework established in the first document of the series “Federal Flood Mapping Framework”, which illustrates the recommended four-step process for preparing flood risk assessments (NRCAN, 2018a). The other key components of the framework are discussed in the remaining documents within the series.

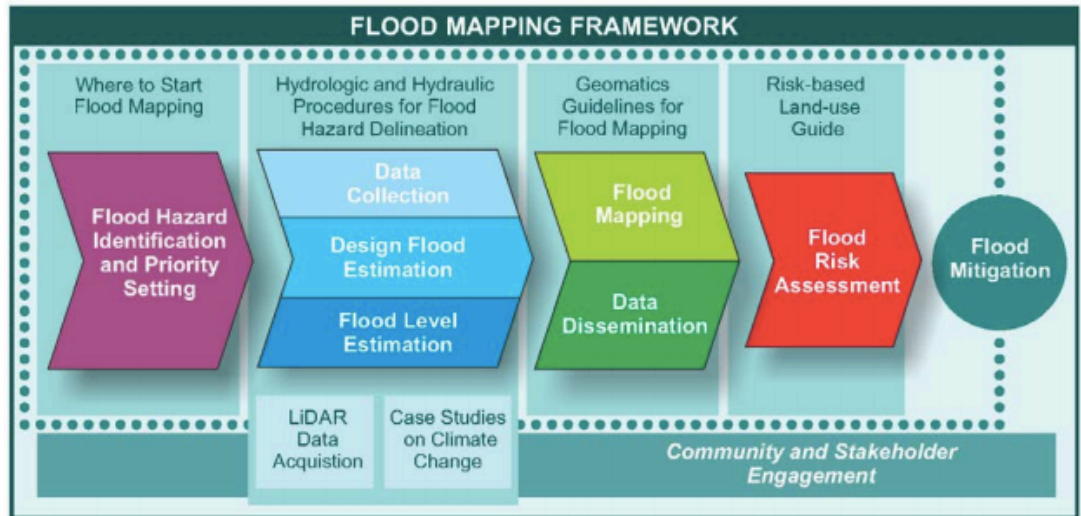


Figure 13: Flood Mapping Framework established by NRCAN (NRCAN, 2018a)

The technical documents in the series include (Natural Resources Canada, 2018a):

- Federal Flood Mapping Framework;
- Flood Hazard Identification and Priority Setting;
- Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation;
- Federal Airborne LiDAR Data Acquisition Guideline;
- Case Studies on Climate Change in Floodplain Mapping;
- Federal Geomatics Guidelines for Flood Mapping;
- Flood Risk Assessment;
- Risk-based Land use Guide; and
- Bibliography of Best Practices and References for Flood Mitigation.

The Federal Flood Mapping Framework document (NRCAN, 2018a) is the first document in the guideline series and introduces the purpose of the series and the proposed flood mapping framework for Canada. The purpose is explained through introducing floodplain maps and discussing the history of floodplain mapping in Canada. The key components of the framework are then established, as seen in Figure 13, and the remaining documents are introduced, as they are derived specifically from the components of the framework.

The second document in the series is titled Flood Hazard Identification and Priority Setting (NRCAN, 2018a). While the document is yet to be published, the purpose of the document is to introduce the first component of the framework that involves identifying and prioritising areas that require floodplain mapping.

The third document in the series is titled Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCAN, 2019a). The document focuses on providing technical guidance on hydrologic and hydraulic applications for floodplain mapping in Canada. With different causes of flooding existing across Canada, the document further informs the reader regarding analysis of common flooding causes, such as ice jams, coastal flooding, and climate change impacts. Geospatial data required to perform hydrologic and hydraulic analysis are introduced, and include elevation, stream, watershed, and surface water network data among others.

One of the data requirements established within the third document is the use of elevation data (NRCAN, 2019a). Light Detection and Ranging (LiDAR) data has been commonly adopted across Canada and is a method used to develop elevation datasets by using pulsed lasers to measure range (NRCAN, 2020). The fourth document, titled Federal Airborne LiDAR Data Acquisition, aims to provide technical notes for consistent application of LiDAR technology and how it can be acquired across all levels of government in Canada.

The flood mapping framework incorporates technical details for estimating the role climate change projections play in floodplain mapping within the hydrologic and hydraulic procedures (NRCAN, 2019a). The fifth document in the series, Case Studies on Climate Change in Floodplain Mapping, aims to provide the reader with projects that have been completed across Canada and where climate change has been applied within the floodplain mapping procedure (NRCAN, 2018b).

The sixth document is titled Federal Geomatics Guidelines for Flood Mapping and this constitutes a resource for professionals vested with the responsibility of distributing the floodplain mapping material (NRCAN, 2019b). Technical specifications for managing and disseminating components of floodplain maps have been discussed. In addition, requirements for data within the different types of floodplain maps are further outlined.

The seventh document titled Flood Risk Assessment is currently under development. It aims to present the reader with technical guidance for performing flood risk assessments across Canada (NRCAN, 2018a).

The eighth document, titled Risk-based Land use Guide, provides instructions on risk-based methodologies for better land-use planning in communities (NRCAN, 2018a). The document has not yet been published, along with other documents in the guideline series.

The ninth and final document in the series is titled Bibliography of Best Practices and References for Flood Mitigation (NRCAN, 2018c). The document contains lists of the best practices for studies pertaining to hydrology and hydraulic, climate change, risk assessment, and floodplain mapping (NRCAN, 2018a). The lists in the document are presented in table format that includes the name of the study and the method to access the study.

## **2.4 Discussion**

Since establishment of the FDR Program, floodplain mapping practices have varied across all provinces and territories. With provincial governments being responsible for their own flood hazard areas production, the guidelines, practices, and availability of floodplain maps vary across the provinces and territories. Table 1 summarises the existing standards and regulations across the country.

The first difference in floodplain mapping practices between the provinces and territories exists within the designated flood magnitude. While Saskatchewan has adopted the largest design flood event of 500-year return period, the majority of provinces are in use of a 100-year return period flood event. Although Calgary which has faced two floods within the last 20 years (2005 and 2013) is still using a 1 in 200-years flood event, it is interesting to note that they have remained with a 100-year return period as the design flood event. Ontario has adopted their design flood standard on a watershed basis due to historical flooding and the vulnerability to flooding events ranging across the province.

The second key difference in mapping practices involves the flood hazard area zonal designation. While the majority of the provinces use a two-zone policy, similar to that discussed in the FDR Program and NRCAN framework, BC remains the lone province to have adopted the one-zone flood hazard area. Newfoundland and Labrador have recently incorporated a three-zone flood hazard area to account for changes in the flood extent resulting from projected climate change conditions. Among the provinces that share a two-zone policy, the determinants for the floodway and flood fringe vary between using two design flood events or identifying flood depths and velocities. Quebec presents different terminology for the two zones, using high velocity zone and low velocity zone to represent the floodway and flood fringe, respectively.

The availability of maps with public access, which identify the areas that are located within the flood hazard zones also varies widely. Currently, one of the more popular techniques employed is the use of an interactive online web service that allows anyone to use and monitor areas that are included within the flood hazard area. This availability of accessible maps then ranges from being historical flood map drawings to no maps presently available. Quebec is the most recent province to include an online interactive web service, which was provided following the 2017 and 2019 flood events.

Table 1: Summary of Floodplain Mapping Practices Across Canada

Province	Design Flood	Flood Hazard Area	Maps Availability	URL	Climate Change Considerations
British Columbia	200 Year	One Zone	Online Tool	<a href="https://maps.gov.bc.ca/ess/hm/imap4m/">https://maps.gov.bc.ca/ess/hm/imap4m/</a>	No Considerations
Alberta	100 Year	Two Zone	Online Tool	<a href="https://floods.alberta.ca/">https://floods.alberta.ca/</a>	No Considerations
Saskatchewan	500 Year	Two Zone	Not Available	NA	No Considerations
Manitoba	200 Year	Two Zone	Not Available	NA	Evaluating methods
Ontario	100 Year or Historic Regional Flood	One or Two Zone	Online Tool or Floodplain Map Drawings	Local Conservation Authority Website	No Considerations
Quebec	100 Year (Low Velocity Zone) 20 Year (High	Two Zone	Online Tool	<a href="https://www.cehq.gouv.qc.ca/zones-inond/ZIS-20190715/index.html">https://www.cehq.gouv.qc.ca/zones-inond/ZIS-20190715/index.html</a>	No Considerations



	Velocity Zone)				
New Brunswick	20 Year (Floodway ) 100 Year (Flood Fringe)	Two Zone	Online Tool or Floodplain Map Drawings	<a href="https://geonb.snb.ca/geonb/">https://geonb.snb.ca/geonb/</a>	No Considerations
Newfoundland and Labrador	20 Year (Floodway ) 100 Year (Flood Fringe)	Three Zone	Floodplain Mapping Studies	<a href="https://www.gov.nl.ca/ecc/waterres/flooding/floodzone.htm">https://www.gov.nl.ca/ecc/waterres/flooding/floodzone.htm/</a>	Climate Change Flood Zone Climate Change Scenarios
Nova Scotia	20 Year (Floodway ) 100 Year (Flood Fringe)	Two Zone	Online Tool	<a href="https://www.arcgis.com/apps/webappviewer/index.html?id=54adf80df5d94459a8ea08554997fa07">https://www.arcgis.com/apps/webappviewer/index.html?id=54adf80df5d94459a8ea08554997fa07)</a>	No Considerations

Prince Edward Island	25m Buffer Zone	NA	Floodplain Map Studies by ACASA	<a href="https://atlanticadaptation.ca/en/islandora/object/acasa%3A627">https://atlanticadaptation.ca/en/islandora/object/acasa%3A627</a> ).	Sea Level Projections included in ACASA maps
Yukon	NA	NA	Not Available	NA	NA
Northwest Territories	100 Year	Two Zone	Online Tool	<a href="https://www.maps.geomatics.gov.nt.ca/HTML5Viewer_Prod/index.html?viewer=ATLAS">https://www.maps.geomatics.gov.nt.ca/HTML5Viewer_Prod/index.html?viewer=ATLAS</a>	No Considerations
Nunavut	NA	NA	Not Available	NA	NA

This chapter has presented the results of the review of floodplain mapping standards and how they vary across provinces and territories in Canada. Three key problems currently exist within floodplain mapping efforts in Canada. The first is the lack of mapping in certain flood prone areas. While the majority of regions across Canada have developed floodplain maps, these maps present discontinuities that lead to smaller communities being ill prepared to face flood risks. The second problem is that the existing floodplain maps at some locations are outdated. With improving technology, changing land use trends, and the increasing magnitudes of flood events, the floodplain maps require updates to best represent the current level of flood risk. The third problem is the public availability of floodplain mapping. With the general public lacking the ability to identify whether their property is exposed to flood risks, they are unable to effectively prepare for and prevent further damage from flooding. Many of these issues have resulted from flood mitigation funding decreasing following closure of the FDR Program.

The production of floodplain maps for national regions can help counteract the existing problems within mapping in Canada. National region floodplain maps have the ability to map the entire country, giving access to all communities that previously lacked floodplain maps. The maps eliminate the need for producing floodplain maps at regional scales, limiting the overall time and cost of their production. The improvements in large region flood maps applications and downscaling approaches are allowing national region maps to be a realistic approach for producing floodplain maps. To identify whether this is a viable option, national region floodplain maps for Canada are analysed further, with appropriate downscaling techniques to perform local studies while retaining high spatial resolution.

### **3. Global Flood Models**

#### **3.1 Description of Global Flood Models**

Global Flood Models (GFMs) simulate flood dynamics to derive flood inundation extent and depths (floodplain maps) at global scales (Bates et al., 2018). Recently, we have seen the use of GFMs increasing due to the evolution of technology and the consequent ability to derive large region floodplain maps (Hoch & Trigg, 2019). GFMs are programmed to solve numerical equations that represent the simulation of the flow of water for fluvial conditions. Historically, GFMs have had difficulties within local scale applications due to their sacrificing detailed information; however, the degree of sacrifice has been reduced in recent years, given increasing computational power and data resources (Sampson et al., 2015). Specific advances in technology and numerical algorithms within GFMs have led to spatial resolution improvement in the derived maps of up to 100 m resolution, allowing more accurate assessment of global floodplain mapping (Ward et al., 2015). The applications of the models range from their ability to be used for identifying current flood hazards at a global scale (Winsemius et al, 2015) to predicting future flood risk due to climatic changes (First Street Foundation, 2020), determining population exposure to the flooding hazard (Mohanty & Simonovic, 2020b), and producing large region floodplain maps that can cover previously unmapped and vulnerable regions.

GFMs incorporate two methodological approaches: cascade model structure and gauged-flow model structure (Aerts et al., 2020). The cascade model structure applies climate forcing data that is developed through historical precipitation datasets and utilises global hydrological models before deriving the desired flood volumes. The development of cascade model structures generally follows a five-step process (as simplified by Trigg et al, 2016): (1) climate forcing, (2) application of a global hydrological model, (3) river flow routing, (5) flood frequency analysis, and (5) downscaling the modelled results. The models are popular due to their ability to produce long time series flow and volume estimates; however, limitations to cascade model structure are that the models can produce results that are biased, uncertain, and require lower spatial resolution (Winsemius et al., 2015).

The gauged flow-model structure involves the use of river discharge datasets for determining the volume of water. Similar to the five-step model introduced for cascade model structures, a five-step process has been developed by Trigg et al. (2016) to establish the construction of this model type as well. The steps include: (1) acquiring global gauged flow data, (2) applying regional flow frequency analysis, (3) deriving flood flow magnitude, (4) developing flood flow routing, and (5) calculating the final flood extent. Issues related to the gauged flow-model structure involve the absence of gauges in particular locations; however, the use of a newly developed clustering methods allows for homogeneous catchments to be grouped together (Sampson et al., 2015).

### **3.2 Data for Global Flood Models**

Depending on the model structure, the data required for the application of GFMs will be differentiated. Cascade model structures first involve the input of precipitation data in the form of climate forcing or flow data in the form reanalysis datasets. When climate forcing data is implemented, a global hydrological model is required to derive the interactions between the ground and atmospheric conditions. Data required to best simulate the flow through river mechanics includes a Digital Elevation Model to represent the topography of land. Additional data sources to determine river geomorphology include river width, river network, flow direction, and global water maps.

Required data for the production of gauged flow-model types is differentiated from the cascade model structure through the input data to derive runoff. Data requirement first involves the usage of data from discharge observations. Various databases, such as the Global Runoff Data Centre, are available and consist of over 9500 stations (Aerts et al., 2020). As with the cascade model structure, a Digital Elevation Model is required to represent the topography for the floodplain. The elevation model can then be used to represent the river geomorphology; however, additional river network and river width maps can be employed if desired.

### **3.3 Existing Global Flood Models**

The increased development of GFMs has allowed for the production of new models to be studied and developed for effective risk assessment. Cascade model structure frameworks, including the Global Flood Risk with Image Scenarios (GLOFRIS) model (Winsemius et al., 2015), present a global flood risk model that is performed for Bangladesh. The European Centre for Medium Range Weather Forecasts (ECMWF) model (Pappenberger et al., 2012) develops a global flood cascade model that presents flood coverage across countries in every province. The final global flood cascade model structure reviewed is the Joint Research Centre (JRC) model (Dottori et al., 2016) that analyses model performance along the Severn, Thames, Niger, Ganges, Mekong, Elbe, Po, Irrawaddy, and Tocantins river basins. Two popular gauged-flow models include the Fathom-Global (Sampson et al., 2015) and Centro Internazionale di Ricerca in Monitoraggio Ambientale (CIMA) (Rudari et al., 2015) models. The Fathom-Global model has been benchmarked along rivers in Red Deer, Calgary, and Edmonton in Canada, and the UK's Thames and Severn catchments, while the CIMA model has been benchmarked for the nations of Colombia, Germany, and Thailand.

The Catchment-based Macro-scale Floodplain (CaMa-Flood) model (Yamazaki et al., 2011) is a cascade model that includes a river routing model used within other GFMs (Hirabayashi et al., 2013; Mohanty & Simonovic, 2020a; Pappenberger et al., 2012; Yamazaki et al., 2011). The CaMa-Flood hydrodynamical model's performance benefits users by allowing them to compute models in reasonable compute times and perform an explicit representation on the flood stage to improve final discharge values (Zhao et al., 2017). Performance index statistics analysed the CaMa-Flood performance for the Amazon Basin, located in Brazil, and thirty other major basins, and presented a good correlation when compared with satellite derived observations (Yamazaki et al., 2011).

### **3.4 CaMa-Flood Hydrodynamic Model for Canada**

The wide use of CaMa-Flood for the application of global hydrodynamic models is due to its ability to simulate large scale flows across the globe well, to generate high resolution gridded flow outputs, to model large scale flow simulations,

and the software being free of charge for research development (Gaur & Simonovic, 2017). Furthermore, the CaMa-Flood is able to accurately model simulated flood dynamics when compared to observational data for large scale catchments (Gaur et al., 2017). Based on this reasoning, the CaMa-Flood hydrodynamic model has been selected for applications on floodplain mapping studies at Western University by both Gaur (2017) and Mohanty (2020a).

Applications of the CaMa-Flood model in research at Western University were first established in studies presented by Gaur et al. (2017, 2018). The studies focused on determining future changes in flood risks resulting from General Climate Models (GCMs). GCMs were used to predict the changes in future flows and flooding projections through simulating complex bio-geophysical and chemical processes in the Earth's Surface (Gaur et al., 2018). 21 GCMs that follow four Representative Concentration Pathways (RCPs) were then implemented in the CaMa-Flood hydrodynamic model to generate streamflow estimates across Canada and the estimates were used to calculate the impact of climate change on flood magnitudes. The results present the current 100-year flood event in South-western Ontario becoming a 10–60-year flood event in the future, while the current 100-year flood event in the northern Prairies is expected to become a 160–200-year flood event in the future.

Western University has since conducted a study with the purpose of producing a national floodplain map that would span across Canada (Mohanty & Simonovic, 2020a). The study focuses on comparing the sensitivities of different reanalysis datasets as input data for the national floodplain mapping framework. It compares four reanalysis sources, which include the Climate Forecast System Reanalysis (CFSR), ERA-Interim, Modern-Era Retrospective analysis for Research and Application (MERRA), and North American Regional Reanalysis (NARR) datasets. The reanalysis datasets are then compared with observed hydrometric data taken from the Reference Hydrodynamic Basin Network (RHBN) to ascertain the degree of uncertainty in the runoff values.

The framework incorporates the CaMa-Flood Global Hydrodynamic Model to establish the river routing mechanism for the floodplain map. River mechanics are

produced through the combination of Flow Direction Map (Yamazaki et al., 2009), Global River Width (Yamazaki et al., 2014), and Global Water Map (Yamazaki et al., 2015), while the topography is formed from elevation inputs from MERIT Hydro (Yamazaki et al., 2019). The final water levels and inundated area are produced through relationships with water storage, while discharge is calculated through the explicit form of the local inertial equation (Yamazaki et al., 2013). Consequent downscaling produced the national floodplain maps at a spatial resolution of 1 km. To perform flood frequency analysis, the Generalized Extreme Distribution (GEV) is applied to the continuous time series data from river flow. This produces floodplain maps for the return periods of 100-year and 200-year flood events. The performed floodplain mapping framework can be seen in Figure 15. The framework presented first establishes the procedure for producing extreme value statistics, before implementing the data in the CaMa-Flood hydrodynamic model. The final steps of the framework involve downscaling the national floodplain maps to a spatial resolution of 1 km and then testing the accuracy of the flood extent with available floodplain benchmark maps and satellite derived floodplain maps. A follow-up study (Mohanty & Simonovic, 2020b) combined the national floodplain map, previously produced, with socioeconomic datasets to identify population exposure across Canada. Datasets included in the study were acquired from Statistics Canada, Global Human Settlement, and the Gridded Population of the World. Spatial resolution of 1 km was available for the three datasets and was selected to prevent issues when projecting the data against the floodplain maps.

Six case study river basins were selected for the purpose of analysing the national floodplain map performance versus benchmark maps. The river basins included the Lower Fraser River Basin, Bow and Elbow River Basin, Assiniboine River Basin, Red River Basin, Grand River Basin, and St. John River Basin. River basins were selected due to a combination of their historical flooding events and current impact from flood inundation events. Following the comparison of four reanalysis datasets and the performance of two return period events, eight floodplain maps were produced for each river basin.

The NARR dataset provided the best performance of the four reanalysis datasets, with a superior hit rate for all six case studies and their respective two return



period events. The hit rate scores resulting from the NARR dataset ranged from a minimum of 0.78 up to a maximum of 0.88, while the critical success index ranged from 0.7 to 0.82 (Mohanty & Simonovic, 2020a). The performance of the NARR derived floodplain map was then compared with historically derived MODIS satellite-derived floodplain maps, which revealed that the model represented more than 75% of the total inundation area (Mohanty & Simonovic, 2020a).

The spatial resolution of 1 km from the national region floodplain maps was adequate for the study, as it allowed for the comparison of the four reanalysis datasets. Due to benchmark maps generally having spatial resolution of 1 km, the accuracy of the flood inundation extent could be calculated through completing performance statistics between the derived nation-scale floodplain maps and available benchmark maps for the six case study river basins. Furthermore, the resolution was effective for performing population exposure studies, as the spatial resolution matched with available socioeconomic datasets. However, the ability of 1 km spatial resolution maps to represent local scale conditions remains inadequate. Practical applications of floodplain maps involve identifying infrastructure and property at risk of flooding, which will allow communities to plan and eliminate the risk of future flooding. Flood proofing measures, development restrictions, evacuation plans, and insurance needs require improved spatial resolution to more effectively determine flood damage at local scales. With spatial resolution of 1 km, the practical application of the floodplain maps at local scales is challenging, as individual properties and infrastructure are lumped together in their 1 km flood depth grid cell.

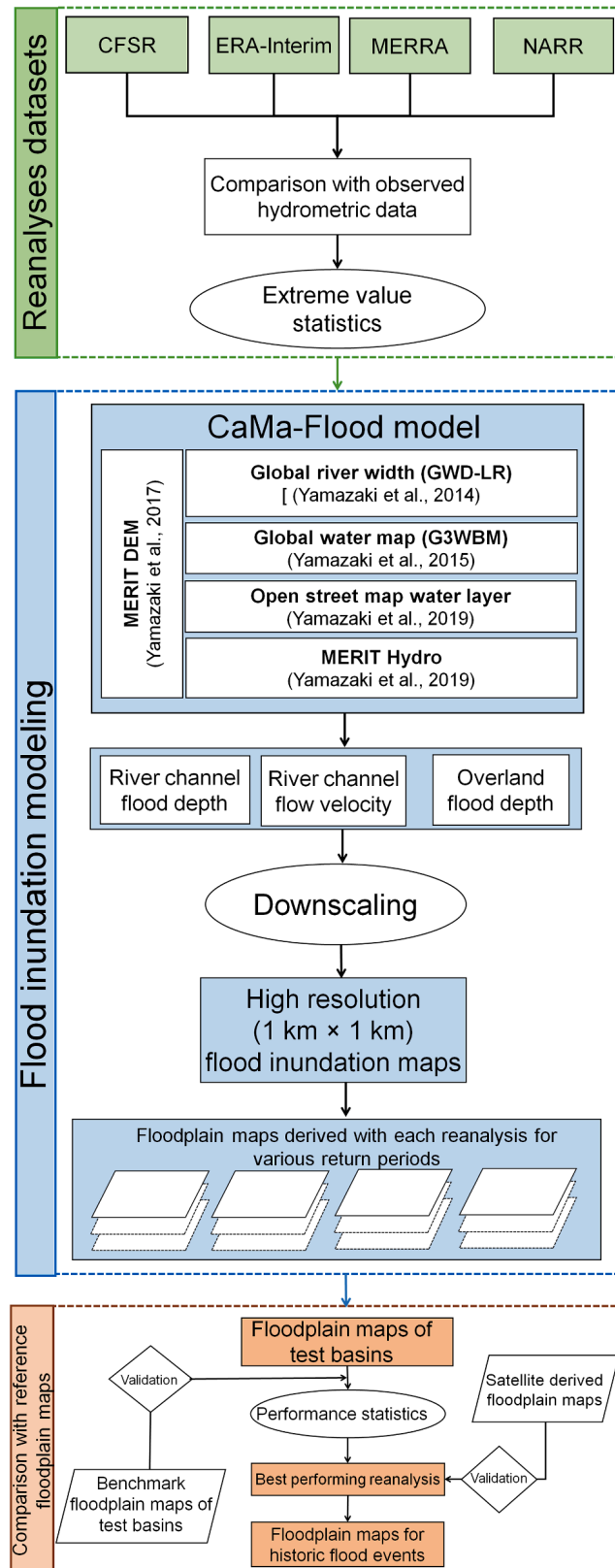


Figure 14: Mohanty and Simonovic (2020a) National Floodplain Mapping Framework

### 3.5 Resolution Issues

Spatial resolution across floodplain maps produced from GFM's varies significantly based on the selected geographical databases, implemented numerical

algorithms, utilised computation power, and the actual requirements. Across the GFMs previously discussed, the GLOFRIS (Winsemius et al., 2015), JRC (Dottori et al., 2016), ECMWF (Pappenberger et al., 2012), and CaMa-Flood (Yamazaki et al., 2011) models have all produced floodplain maps at a spatial resolution of 1 km, while the FATHOM-Global (Sampson et al., 2015) and CIMA (Rudari et al., 2015) have produced floodplain maps at a spatial resolution of 90 m. The required resolutions of the global scale floodplain maps vary depending on their practical applications. The application of GLOFRIS was to identify global flood risks and the floodplain maps were matched with socioeconomic data of 1 km resolution to perform the flood risk assessment. The floodplain maps produced in the JRC study required a 1 km resolution to test the sensitivity of the modelling framework by comparing the floodplain maps to available benchmark maps at 1 km resolution. However, when applying floodplain maps to local scale, there is a further need for spatial resolution finer than 100 m to retain valuable flood mapping detail, so as to best identify flood risks (Schumann et al., 2013).

Although GFMs have seen improvement in spatial resolution within the floodplain maps by up to 100 m resolution, constraints still exist in producing high resolution floodplain maps in global scale studies (Ward et al., 2015). Issues of spatial resolution stem from the accuracy of boundary conditions and Digital Elevation Models with regard to river dynamics detail (Ward et al., 2015). The choice of GFM model type plays an additional role in the output spatial resolution, as cascade models tend to support only low resolution (Winsemius et al., 2015), and downscaling is often required to improve the final output resolution to 1 x 1km grid scales (Aerts et al., 2020; Dottori et al., 2016; Winsemius et al., 2015). GFMs which are further used to address exposure and vulnerability may also require higher spatial resolution to match the existing resolution of databases that are implemented alongside the maps (Rudari et al., 2015).

The National Floodplain Mapping Framework, introduced in Section 3.4, presents an approach that derives floodplain maps across Canada at a spatial resolution of 1 km and identifies the accuracy of the mapping with analysis of six river basins' case studies. Although the resolution was sufficient to perform a reanalysis dataset study (Mohanty & Simonovic, 2020a) and a population exposure

study (Mohanty & Simonovic, 2020b), the final spatial resolution impacts the ability of the floodplain map to facilitate local land use decisions for infrastructure development and the identification of current levels of property exposure. For large region floodplain mapping to be an appropriate replacement for local scale mapping across Canada, the final spatial resolution for the maps must be improved to enable better identification of property and infrastructure exposure to flood risks. This will allow communities across Canada to implement the floodplain maps more effectively when finalising flood insurance, damage assessment, floodplain regulations, and emergency preparedness.

#### **4. Description of Floodplain Mapping Downscaling Methodologies**

The procedure for improving the spatial resolution of floodplain maps is known as downscaling. With the application of large region floodplain mapping rapidly increasing for global flood risk studies, downscaling methodologies are becoming a valuable tool to increase the spatial resolution of floodplain maps for implementation at local scales. Three of these downscaling methodologies are identified as the most appropriate fit to apply to the national region floodplain map produced by Western University. The downscaling methodologies reviewed include the GLOFRIS, First Street Foundation, and a two-tiered downscaling methodology.

##### **4.1 GLOFRIS Downscaling Methodology**

The GLOFRIS Framework, propounded by Winsemius et al. (2015), involves a two-step process for the completion of a global flood risk assessment. The first component of the framework involves the production of a global hydrologic and flood-routing model before the global flood inundation map can be downscaled to the appropriate scales for assessment. The second involves measuring the hazards and risks of the event through the incorporation of socio-economic indicators (including GDP, population, and annual exceedance damage). This methodology is implemented in Bangladesh with an appropriate return period to visualise the potential impacts of a damaging flood event.

The global flood statistics are produced through the combination of the global hydrology model PCR-GLOBWB, global hydraulic model PCR-GLOBWB with the dynamic routing extension DynRout, and required forcing using a 30-year dataset. The global flood statistics are post processed into the annual statistics of maxima to produce the results for the final global flood inundation map. The global flood model has a final spatial resolution of  $0.5^\circ$ , matching the spatial resolution of the hydrologic PCR-GLOBWB model. One of the requirements for the floodplain map routine consists of adopting an assumption regarding the non-impact flooded volume, which allows for the consideration of a certain volume of water without impacting the surrounding areas. The permissible flooded volume of water is determined by subtracting the calculated flood event where no flooding occurs from the total flooded

volume of the chosen probabilistic event. The non-impact flood event is considered as the safety level for the GLOFRIS framework.

To improve the global floodplain map resolution, a mass conservative downscaling approach is established to improve the resolution to 1 km x 1 km. The downscaling process begins with inputting a user-selected stream order threshold, determining which ones are considered river cells. Subsequently, a specific water elevation is imposed above the level of the river on the river cells within the spatial resolution 0.5°. All upstream connected river cells are evaluated to determine whether the cell is flooded by subtracting the high-resolution surface elevation from the low-resolution water elevation, imparting each high-resolution cell with a flood depth. The procedure is then repeated through an iterative process of increasing the imposed water elevation until the flood volume of water from the elevation equals that of the 0.5° cells from the low-resolution floodplain map.

Two main inputs – the stream order threshold and safety level – were identified to be generating the greatest impacts on the downscaling results. Due to the selection of a lower stream order threshold, the amount of river cells increased as the stream order identified more river channels that will be subsequently flooded. As a result, the final area where the coarse resolution flooded volume is spread over increases. The safety level chosen in reducing the global flooded volume also impacts the final results as it reduces the flooded volume being spread out. The overall impact due to the selection of a different safety level is considerably smaller than the one for the selection of the stream order threshold.

The mass conservative flood inundation downscaling technique was later adapted to use within the Aqueduct Floods Methodology study (Ward et al., 2020). The Aqueduct Flood Risk Analyzer was launched in 2015 as an innovative tool to determine flood risks on a global scale. Flood risk projections include future climate conditions and risks involving both riverine and coastal conditions. Similar to GLOFRIS, floodplain maps in the study were downscaled to 30'' x 30'' spatial resolutions (approximately 1 km). The downscaling process made one adjustment where the user-selected minimum stream order threshold produced a Height-Above-Nearest-Drainage model for identifying the river cells to be flooded. The flooded

volume from the low-resolution map was then spread out over the 30" x 30" Digital Elevation Model (DEM) to produce the downscaled floodplain map (Ward et al., 2020).

#### **4.2 Fathom-US Downscaling Methodology**

First Street Foundation and Fathom Global collaborated together in efforts to identify areas of flood risk across the Continental United States (First Street Foundation, 2020). The national floodplain map is produced using the Fathom Model framework. The framework for procuring the floodplain map includes the historical, present, and future scenarios for evaluating flood risks. Future flood risks consider recommendations from the Intergovernmental Panel on Climate Change (IPCC) for climate change scenarios. The methodology includes efforts into assessing flood risks from both inland and coastal flood events.

The Fathom framework primarily comprises of the construction of the Fathom hydraulic model using the LISFLOOD-FP software (First Street Foundation, 2020). The hydraulic model is a raster-based two-dimensional shallow water model that can incorporate a fine resolution DEM to simulate flows. Channels within it are represented using a 1D sub-grid representation to allow for any river size to be included within the modelling. The Regional Flood-Frequency analysis is completed to establish the flows for chosen return period magnitudes by utilising the flows calculated from historical gauge records. The final outputted hydraulic simulations were completed at a spatial resolution of 1 arc second (approx. 30 m).

To enhance the spatial resolution of the final floodplain map, a downscaling approach conserving the water surface heights from low-resolution to high-resolution maps was executed. The approach begins by taking the water surface heights from the low-resolution map, the water surface elevations at the boundaries of which are then extended by 1 cell. Using a DEM with a finer resolution than the map, the water surface elevations are resampled on to the high-resolution DEM using bilinear resampling, resulting in the production of the new water surface elevation mask. Subtracting the DEM values from the water surface elevation mask produces the downscaled flood depths. Any flood depth with values less than 0 m are corrected to 0

m and any water cells not connected to another are corrected to 0 m to avoid the potential for discontinuities. The final floodplain map produced spatial resolutions of approximately 3 m.

#### **4.3 Sub-grid Two-Tiered Downscaling Methodology**

Due to the current state of technology, large region floodplain maps require a lower spatial resolution to produce results for reasonable compute times. Conflicts are then created with the need to retain details only presented in high resolution models. As a result, Guy Schumann et al. (2013a) proposed a two-tiered floodplain map downscaling methodology that involves downscaling both in the channel and floodplain sections. The methodology was tested along the Scioto River, a major tributary of the Ohio River, USA, with the model area covering over 2,150 km<sup>2</sup>.

A large scale 2D hydrodynamic model was constructed by employing the National Elevation Dataset (NED) which covered the entirety of the Scioto River, USA. The model was simulated within the LISFLOOD-FP using a regular grid structure. Additionally, channel depths were also simulated within it using hydraulic geometry and a sub-grid channel routine, all within the software. The main use of the routine was to allow the accurate simulation of channels where the river widths and lengths are not accurately represented by the DEM. Cross-sections were constructed perpendicular to the channel direction to obtain its widths, to ensure the accuracy of which, the cross sections were clipped to the outer boundary of a Landsat-derived water mask. The final floodplain map was produced with a 600 m spatial resolution.

The large region floodplain map proceeds through a two-tiered downscaling methodology, with the first tier considering downscaling in the 1D channel and second considering downscaling in the 2D floodplain. The first step involves the first tier of downscaling; water surface elevations simulated in the large region floodplain map are projected over the constructed cross-sections of the channel. The water surface elevations are then interpolated linearly across the cross-sections. The second tier of downscaling begins with identifying all wet floodplain cells in the low-resolution map. Once found with their respective water surface elevations, they are compared to the high-resolution elevation data for which cells occupy the same low-



resolution cell. All elevations less than the water surface elevation are ignored. The 1D channel downscaling results are used to fill out the remaining no data positions of the 2D floodplain map where the 1D channel occupies water surface elevation data. The downscaled water depths can then be calculated through subtracting the high-resolution elevation data from the high-resolution water surface elevation data. To ascertain that the downscaling methodology meets mass conservative conditions, the combination of a region-growing algorithm and spawning constant – which determines the growth rate in iterations – is used to conserve the flood volume after downscaling. The final resolution for the floodplain map after downscaling holds a 90m grid resolution.

The results of the paper by Guy Schumann et al. (2013a) presented the downscaling performances which produced a difference of 7.85% in the prediction compared to the reference floodplain mapping data, where the prediction accurately includes the precise dry and wet cells. The methodology performance for the 2D floodplain downscaling approach depicted a correct prediction difference of 7.96%, presenting the ability of the downscaling approach to be effectively used without the need to downscale in the 1D channel. Large scale floodplain maps would require a compute time of 1.5 days to produce high-resolution results for a one-year hydrograph compared to the time of one hour when the two-tiered downscaling is used.

#### **4.4 Discussion of Downscaling Methodologies**

The previous discussion presented three different downscaling approaches to improve the large region floodplain map resolutions. The GLOFRIS downscaling methodology involves iteratively imposing water levels to determine the flooded cells. The flood extents derived from downscaling displayed similar satellite-derived flood extents obtained from the Dartmouth Flood Observatory database. However, the downscaling methodology is limited to improving the spatial resolution of the floodplain maps to 1 km in both the GLOFRIS and Aqueducts frameworks. With the current national floodplain map produced at 1 km spatial resolutions, the performance of this downscaling methodology in improving spatial resolutions beyond 1 km is unknown, limiting the applicability of the GLOFRIS downscaling methodology for improving the spatial resolution of the national region floodplain map.

The First Street Foundation put forward a statistical methodology through the application of bilinear resampling of the water surface elevations of the low-resolution models to produce a high-resolution floodplain map. The methodology is simple to implement and downscales the water depths to spatial resolutions of 3 m, allowing high-resolution maps for local studies. However, the maps' initial spatial resolution is 10 m, which already includes high-resolution details and does not require accounting for the difference in elevation terrain features that would be needed for downscaling the national floodplain map.

The final downscaling methodology reviewed the two-tiered downscaling, returning high accuracies in the downscaled flood extent when compared to reference maps. The methodology focuses on downscaling in both the 1D channel and 2D floodplain before deriving the downscaled depths through calculations of overtopping. The floodplain map spatial resolution is downscaled from 600 m to 90 m, which represents both a similar starting spatial resolution to that of the national floodplain map and a similar desired downscaled resolution. The results of the downscaling methodology for the 2D floodplain presented high accuracies for the flood extent similar to the flood extent accuracies within the two-tiered downscaling.

After completing an analysis of the three downscaling methodologies, the 2D downscaling method within the two-tiered downscaling methodology has been chosen for implementation to improve the spatial resolution of the national region floodplain map. The methodology presents a study depicting high accuracy downscaling and includes a large region floodplain resolution similar to that of the national floodplain map and a downscaled spatial resolution that can represent flood risks for local scales.

## **5. Implementation of Downscaling for National Floodplain Map**

Before large region floodplain maps possess the ability to replace individual local-scale floodplain maps, the maps' final spatial resolution require further improvements to be applicable to local-scale studies. The national region floodplain map developed by Western University is highly accurate and spans across Canada. The map's 1 km spatial resolution illustrates the ability to identify population exposure to the design flood events; however, the resolution must be improved to further identify individualised infrastructure and property exposure of the design flood events. This would improve the ability of the maps to be practically applied for flood-proofing measures, floodplain development restrictions, insurance assessments, and emergency preparedness at community and local scales. To allow the map collection to analyse local-scale flood risks, a floodplain mapping downscaling methodology is necessary to improve the final spatial resolution.

Following the assessment of the downscaling methodologies, the two-tiered downscaling methodology has been chosen to be implemented within two selected river basins from the national region floodplain map. The methodology was chosen due to its ability to downscale flood depths and water surface elevations, derive accurate flood extents, and produce spatial resolutions adequate for local-scale floodplain studies. The ability to further implement the methodology solely for the 2D floodplain additionally confirms its potential applicability within the national region floodplain map river basins. The following chapter discusses the chosen case studies, required data inputs, and proposed downscaling process.

### **5.1 Study Areas**

#### **5.1.1 *Calgary Case Study***

The City of Calgary, Alberta is located in a basin made up of two rivers – the Bow and Elbow Rivers. They begin in the Rocky Mountains before coming to a confluence in city where the river basin is established, the total drainage area of which is approximated to be 1,345km<sup>2</sup> (Mohanty & Simonovic, 2021a); the boundaries for the river basin can be seen in Figure 15.

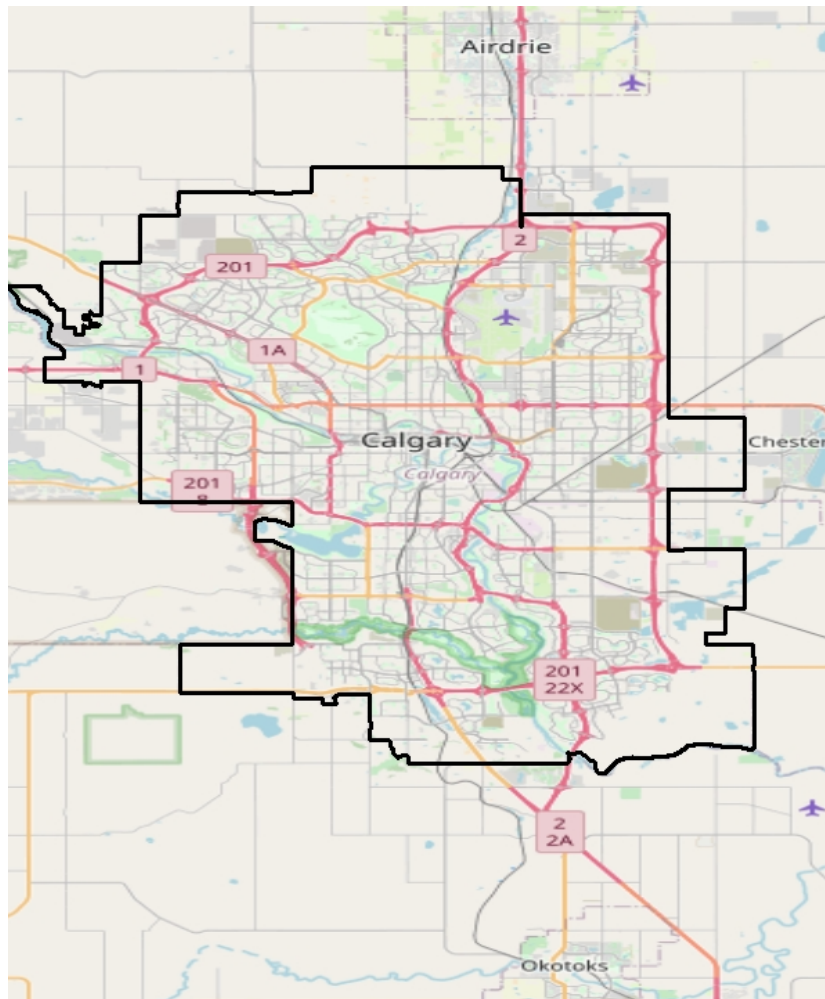


Figure 15: Boundary of the Calgary Case Study

The river basin has experienced severe flooding from two major flood events that occurred in 2005 and 2013, with the latter becoming Western Canada's largest disaster loss on record at the time (Kovacs & Sandik, 2013). The event was caused initially as a result of heavy rainfall in combination with an enormous snowpack located along the Rocky Mountains. The constant, intense rainfall lasted from June 19<sup>th</sup> to 21<sup>st</sup> and continued to increase the already high level of runoff in the basin, resulting in total damage recoveries following the event an exorbitant \$6 billion (Environment and Climate Change Canada, 2017). Spring flooding is an annual concern for the river basin as a result of the Bow River's starting point. With the river basin vulnerable to annual flooding, this information allowed both the river basins to be chosen as a suitable case study area for developing increasingly high-resolution

floodplain maps. For the purpose of this study, the extent of the basin is the City of Calgary's boundary area.

### ***5.1.2 New Brunswick Case Study***

The St John River Basin acts as both an international and interprovincial basin, existing in the state of Maine, USA and provinces of Quebec and New Brunswick, Canada. The Saint John River is the primary river in the basin, extending from its upstream beginning in the Little John Lake in Maine to its drainage point at St John (Newton & Burrell, 2015). The river basin has an established drainage area of 12,222 km<sup>2</sup> for New Brunswick (Mohanty & Simonovic, 2021a) and the boundaries for the river basin implemented in the study are presented in Figure 16.

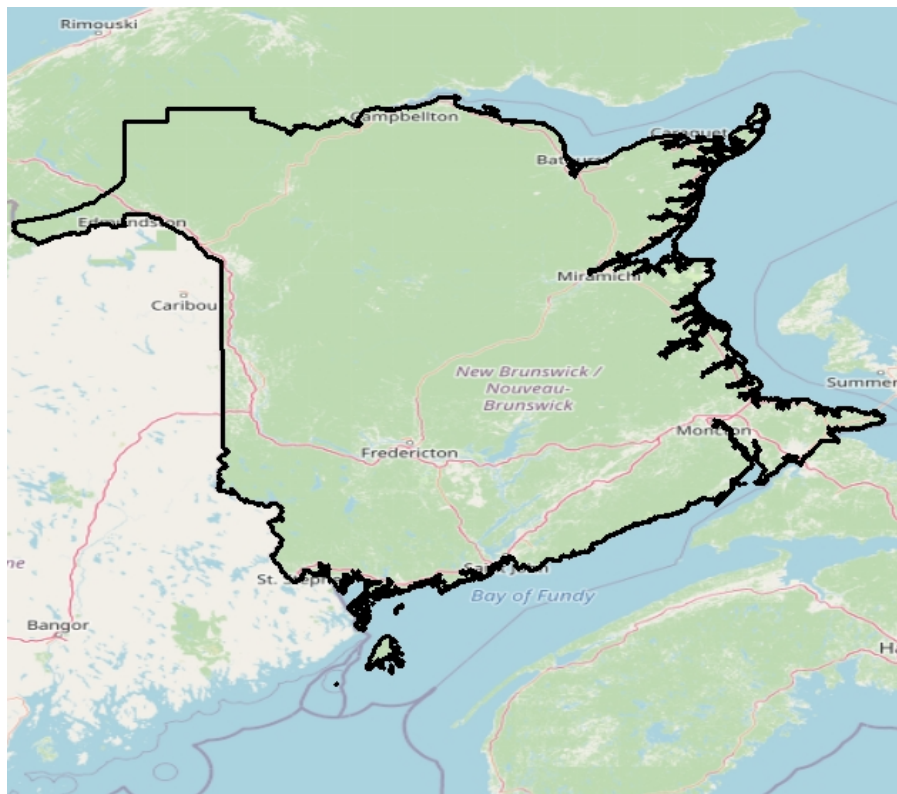


Figure 16: Boundary for the New Brunswick Case Study

Spring flooding in 2008 along the St John River impacted 600 properties beyond repair and resulted in damages with an exceedance of CAD \$23 million (Newton & Burrell, 2015). Higher than average snowfall amounts were presented in snow surveys of that year; however, the degree of the flood extent had still not been

expected (Newton & Burrell, 2015). New Brunswick has seen further flooding events as recently as 2018, due to the increased snowfall in April. Precipitation events later combined with a large snowpack and the flood event saw high flow levels above the flood stage for a total of 14 days (Boisvert & Government of New Brunswick, 2020). Recent flooding events have made New Brunswick the ideal case study for examining the effectiveness of large region floodplain mapping and consequently, the downscaling of the maps to improve the resolution. For the purpose of this paper, the St John River Basin has been established as the boundary of the Province of New Brunswick, providing two case studies to compare the impacts of the downscaling methodology for city - and provincial region case studies.

## **5.2 Data Requirements**

The data required for the downscaling methodology consists of a DEM and a low-resolution floodplain map. The DEM, CanElevation series, was obtained from open government data from the Government of Canada ([https://ftp.maps.canada.ca/pub/elevation/dem\\_mne/highresolution\\_hautresolution/](https://ftp.maps.canada.ca/pub/elevation/dem_mne/highresolution_hautresolution/)). It includes a high-resolution elevation model with spatial resolution options of 1 and 2 m derived from airborne Light Detection and Ranging (LiDAR) data and satellite images. The data can be downloaded by selecting the Digital Terrain Model and desired spatial resolution before choosing the region of choice. For the intents of the case study, the elevation model has been clipped to the boundary areas of the two case studies. The low-resolution national floodplain map has been obtained from the research from Western University (Gaur et al., 2018; 2019; Mohanty & Simonovic, 2021a; 2021b). The national floodplain maps that implemented the NARR reanalysis data were chosen due to their high performance in the Mohanty and Simonovic study (2021a). Four case study maps have been selected, which include the 100-year and 200-year return period for both study areas. It is important to note that the two return periods for Calgary have a spatial resolution of 500 m, while it is 1000 m for the New Brunswick ones. This note becomes important during the results and discussion of the final downscaled floodplain maps.

### **5.3 Downscaling Methodology**

The downscaling methodology involves key components from the two-tiered downscaling methodology proposed by Guy Schumann (2013a). The process to be implemented removes the first tier of the downscaling process, 1D channel downscaling, and focuses on downscaling within the 2D floodplain. This approach was adopted due to the performance of downscaling within the 2D floodplain depicting a limited 0.11% difference in the correct prediction for the coverage of the flooded event when compared to the one for downscaling the 1D channel and 2D floodplain together. All codes written for the downscaling and post-downscaling approach are applied within MATLAB (available in appendix B), with pre-processing steps completed in ArcMap.

The applied methodology is described in detail in the following sections and a visual representation of the framework is displayed in Figure 17. The framework presents the two key inputs required for the downscaling methodology before discussing the major procedures of the framework to derive the higher resolution floodplain maps. A visual representation of the downscaling methodology is presented in section 5.4.

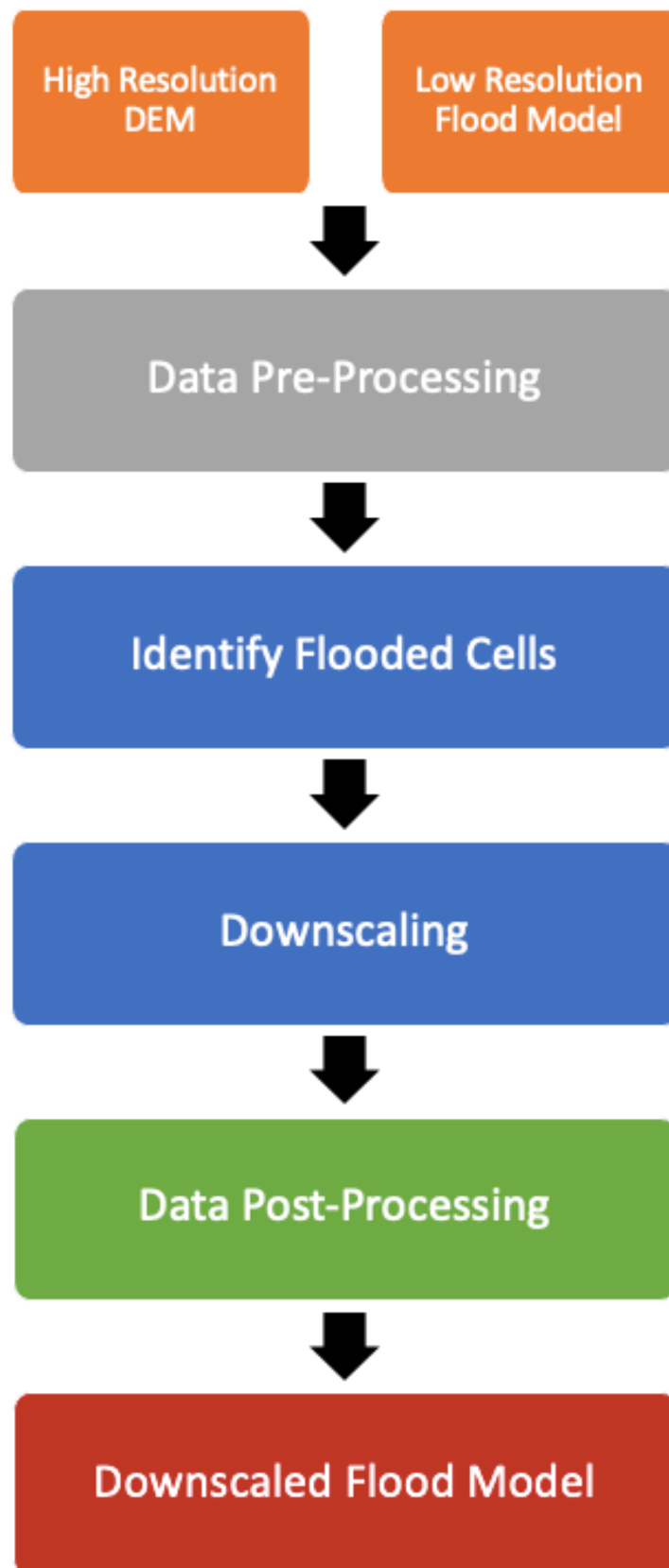


Figure 17: Implemented Downscaling Framework



### **5.3.1 Data Pre-Processing**

The pre-processing steps are utilised to ensure the data is formatted consistently for use within MATLAB as well as to reduce the overall computational time of the downscaling approach.

The first step involves applying a floodplain buffer to the DEM, which is the area that covers the floodplain and area around the flooded region. The purpose for the floodplain buffer is to reduce the computational time in the downscaling methodology in MATLAB, as this reduces the overall size of the elevation data. A polygon shape, which represents the floodplain buffer, is created and surrounds the floodplain region where the flooded cells exist. The DEM is then clipped to the newly created floodplain buffer to reduce its size.

The next required input for the downscaling approach is the low-resolution water surface elevation map that is constructed through the combination of the national floodplain map and DEM. The low-resolution floodplain map undergoes masking to produce an isolated water depth mask consisting of only the flooded cells with their respective flood depth values. The DEM is then extracted by the water depth mask to contain elevation cells that overlap solely with the flooded cells from the low-resolution floodplain map. To produce the final low-resolution water surface elevation map, the isolated flood depth mask is added to the elevation mask. The final resolution of the water surface elevation map is that of the low-resolution floodplain map. This step is completed for both the 100-year and 200-year return periods for both river basin floodplain maps.

Once both the water surface elevation map for flooded pixels and reduced DEM have been produced, the two files and low-resolution floodplain maps are converted to the ASCII format. This is completed to import the files to MATLAB using the ASCII reader MATLAB function, readily made available by LISFLOOD-FP ([https://source.gy.bris.ac.uk/wiki/LISFLOODFP\\_and\\_MATLAB#File\\_import\\_and\\_export](https://source.gy.bris.ac.uk/wiki/LISFLOODFP_and_MATLAB#File_import_and_export)). The reduced DEM is then further aggregated to resolutions of 40 m, 60 m, 80 m, 100 m, 200 m, 300 m, and 400 m to perform an analysis on the

sensitivity of the final downscaling resolution, as the reduced DEM resolution is its determinant.

### **5.3.2 Downscaling Methodology**

The downscaling methodology follows a similar process to that of the 2D downscaling methodology implemented in the floodplain from the two-tiered downscaling study (Schumann et al., 2013a). Introduced within the methodology is a scattered interpolant to evaluate the downscaled flood depths where they are greater than the prior water depth of the low-resolution floodplain map. The final inputs required for the downscaling methodology are the high-resolution reduced DEM, low-resolution water surface elevation map, and low-resolution floodplain maps.

The three inputs are imported to MATLAB using the ASCII reader function, establishing the properties for their respective data, cell size, and geographical extent. This produces three matrixes that undergo a process to convert the data to a 2D vector format, consisting of longitude and latitude points and their respective data. All vector positions where the low-resolution water surface elevation cells coexist with the high-resolution reduced DEM elevation cells are found, following which the water surface elevation map is reprojected to that of the DEM resolution. The same process for finding coordinate positions is then repeated for the high-resolution reduced DEM and low-resolution floodplain map, reprojecting the floodplain map to that of the resolution of the DEM. Each cell from the water surface elevation map then goes through a process for overtopping to identify whether the cell is considered flooded or non-flooded. The elevation from the DEM is subtracted from the water surface elevation to produce flood depths, and overtopping is determined for all flood depths with a value greater than zero. The cells that experience overtopping are identified as flooded cells. All flood depths less than zero are adjusted to zero to account for the non-possibility and categorised as the non-flooded cells.

Depending on the resolution of the DEM compared to that of the low-resolution floodplain maps, the downscaled water depths have the potential to be far greater than the realistic depth. This is a result of the changing elevation that can exist in the one grid space dimension of the water surface map. As such, a measure has

been introduced using a scattered interpolant to ensure that all downscaled flood depths are enforced by the respective low-resolution flood depth cells they occupy. All downscaled flood depths that are less than or equal to their respective low-resolution flood depth cells are found and considered the original flood depths. Subsequently, they are inputted to the scattered interpolant alongside their respective vector positions. The original flood depths are added to a new matrix column with vector positions matching the high-resolution reduced DEM. All downscaled flood depths that are greater than their respective low-resolution flood depth cells are found and the scattered interpolant applies the nearest neighbour interpolation and extrapolation methods using the large downscaled flood depths. This, in turn, produces new corrected downscaled flood depths for each one found to be too large, which are then added to the matrix column alongside the original downscaled flood depths. The original and corrected downscaled water depth columns must then be added together to form the final downscaled water depths for the high-resolution floodplain map. It is important to note that due to the vector format for the high-resolution floodplain map, the format should be converted to a matrix of rows and columns representing the latitude and longitude of the covered area – this allows for the ability to display the final downscaled flood depths in map format as well as export the map for display in ArcMap. For exporting, the ASCII\_write function from LISFLOOD-FP can be used ([https://source.gy.bris.ac.uk/wiki/LISFLOOD-FP\\_and\\_MATLAB#File\\_import\\_and\\_export](https://source.gy.bris.ac.uk/wiki/LISFLOOD-FP_and_MATLAB#File_import_and_export)).

### ***5.3.3 Post-Processing of the Downscaled Data***

Two main conflicts arise following the downscaling methodology that must be both reviewed and addressed to improve the accuracy of the high-resolution floodplain map. These conflicts are discussed before introducing the two techniques employed for improving the high-resolution floodplain maps, which are implemented within MATLAB and the inputs are in the format of ASCII files.

The first conflict to arise involves the ability for high-resolution flooded cells to exist outside the low-resolution floodplain map cells. During the downscaling process, the only high-resolution cells considered flooded cells are the high-resolution cells that exist within low-resolution cell area. This automatically prevents any high-

resolution cells outside the low-resolution flood cell area to forgo the flooding process. In reality, the potential for flooding is extant within the high-resolution cells that exist outside the downscaled flooded area.

The second conflict arises through ensuring the methodology is mass conservative. Mass conservation, involved in floodplain mapping downscaling, requires the final discharge or volume of the downscaled map to be equal to the same of the low-resolution map. This ensures that the full volume of flooded water is accounted for. However, the downscaling process used focuses primarily on the reprojection and calculation of water surface levels from the low-resolution to the high-resolution cells. This creates the potential for the flooded volume to differentiate between the high-resolution and low-resolution floodplain maps and can lead to the final downscaled volume estimates to be lower or in some cases, as to be discussed later, higher than the volume from the low-resolution map.

Two approaches are adopted to ensure the conflicts are resolved within the post-processing steps of the downscaling methodology. The first approach involves a method to identify non-flooded cells that have elevations less than the water surface level of their neighbouring flooded cells. The downscaled water depths are added to the elevation data from the reduced DEM to produce the downscaled water surface elevation for each flooded cell. Non-flooded cells to flooded cells are checked for flooding conditions. All non-flooded cells with elevations less than the water surface elevation of their adjacent flooded cell are then identified as flooded cells. The newly declared flooded cells are provided a water depth of their elevation subtracted from the water surface elevation of their adjacent flooded cells. This process is repeated until all non-flooded cells in the reduced DEM are identified as remaining non-flooded or flooded. The process is limited to non-flooded cells to ensure the depths within flooded cells remain consistent through this approach. It is important to note that for this part of the approach, the dimensions of the ASCII matrix for the high-resolution downscaled floodplain map must be identical to allow the elevation matrix to be effectively added to the water depth matrix to produce the final water surface elevation matrix.

The second approach involves a volume check method to ensure the downscaled floodplain map is mass conservative with the low-resolution floodplain map. Once the first post-processing approach is applied, the second approach first discerns all flooded cells in the downscaled floodplain map. The downscaled volume and low-resolution volume are calculated by taking the total water depth and multiplying this by their respective cell areas. Downscaled water depths are then iteratively increased until the two flooded volumes are equal, making the final downscaled map mass conservative. Depending on the volume accuracy of the downscaled map, the flood depth iterative difference required for mass conservation condition varies across downscaled floodplain maps.

#### 5.4 Illustrative Downscaling Methodology Example

To demonstrate the downscaling process further, a region along the Bow River of the low-resolution floodplain map has been selected to illustrate the application of the downscaling methodology. The selected region has been highlighted in Figure 18 in the boundary of the Calgary case study.

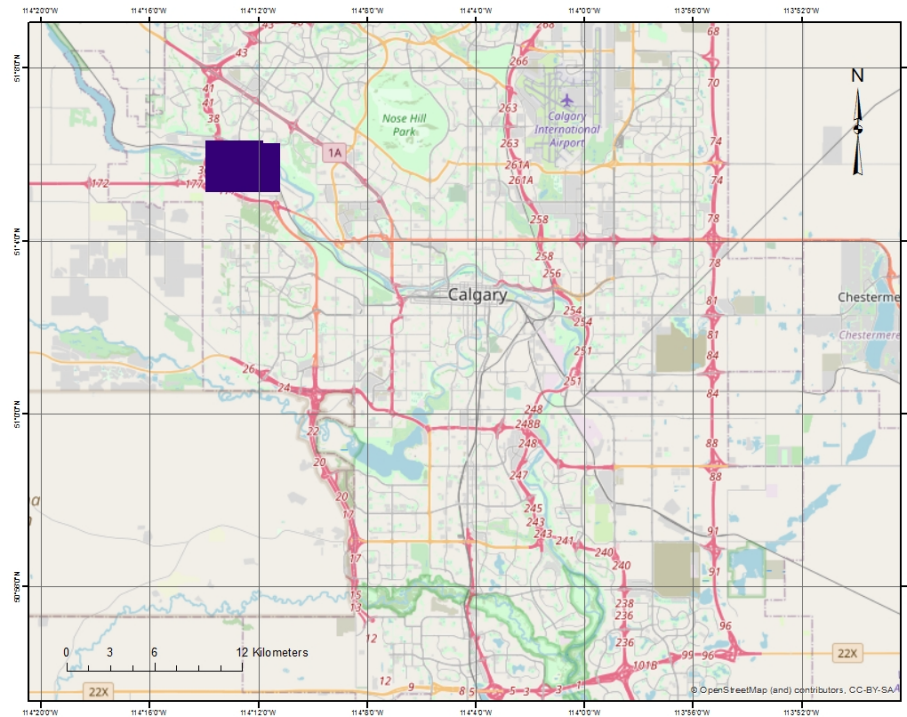


Figure 18: Selected region for the illustrative downscaling process. The selected region is highlighted in yellow.

The low-resolution floodplain map and DEM for Calgary are clipped to the boundary area. Due to the region's limited size, the application of a floodplain buffer to reduce the size of the DEM is not performed. The water surface level map is produced by further clipping the DEM to the flooded cells of the low-resolution floodplain map and adding the resultant clipped DEM to the low-resolution floodplain map. The clipped DEM is displayed in Figure 19 and presents the varying land surface elevation of the selected region with a colour scale to the right. It includes a total of 1000 high-resolution land elevation cells. The clipped low-resolution floodplain map is depicted in Figure 20 and the low-resolution water surface level map can be seen in Figure 21. The two figures present the varying flood depth (blue) and water surface level (red) with a colour scale next to the maps. Eleven low-resolution cells occupy a flood depth and water surface level value in the selected region out of a potential 40 cells that account for the entire selected region. For all three maps below, the y and x axis represent the cell number. It is important to note that the two low-resolution maps present the low-resolution flooded cells and their geographical locations are identical.

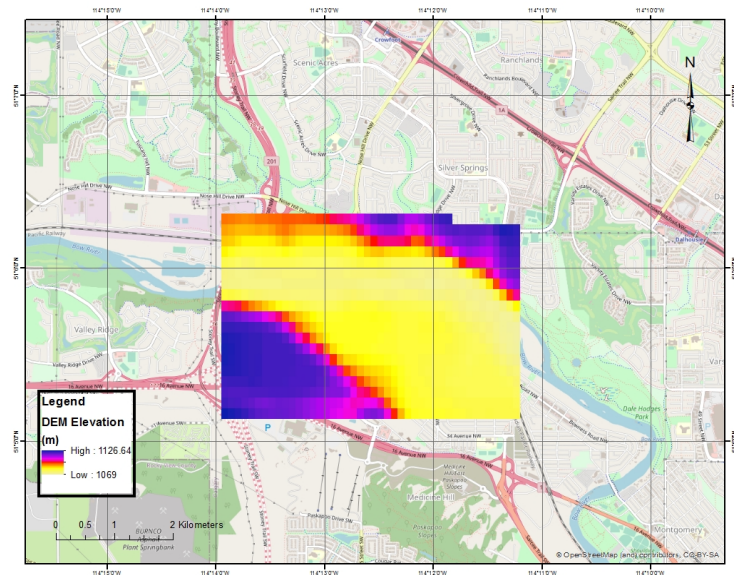


Figure 19: Clipped Digital Elevation Model for the selected region



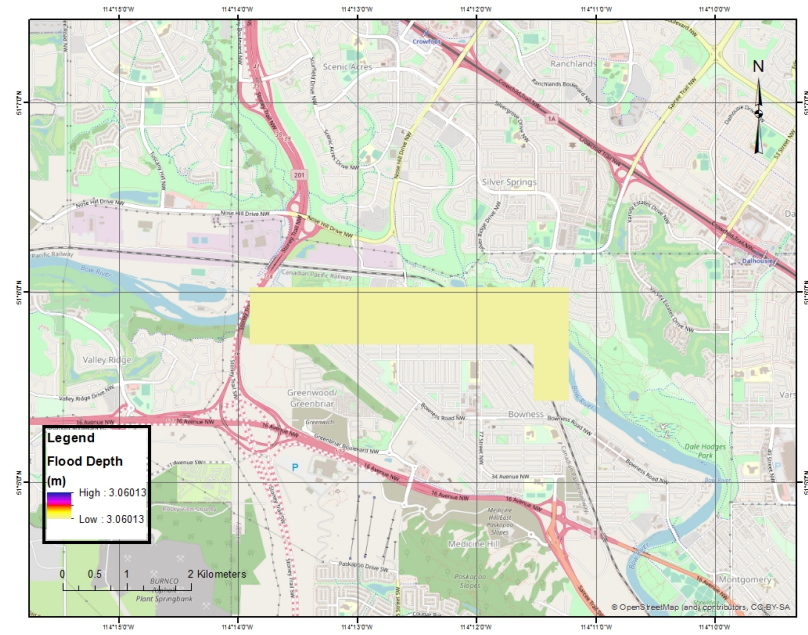


Figure 20: Clipped low-resolution floodplain map for the selected region

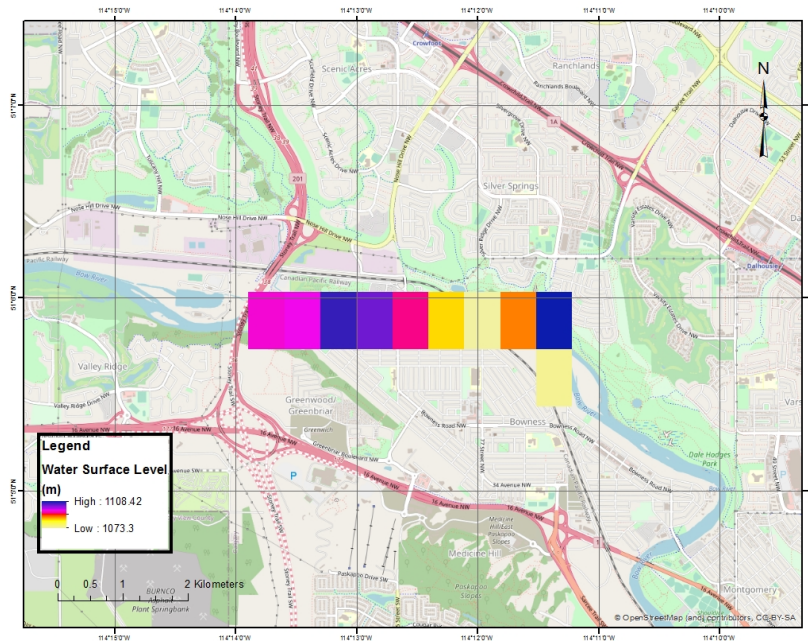


Figure 21: Clipped water surface level map for the selected region

Following the pre-processing steps, the DEM, low-resolution water surface level map, and low-resolution floodplain map are imported into MATLAB to undergo the downscaling methodology. Both low-resolution maps are resampled to the resolution of the DEM using the nearest neighbour approach to improve the number of

cells in the low-resolution maps to match the high-resolution maps. Based on the newly resampled water surface level map, the computational procedure finds the elevation cells that overlap with the flooded cells. The geographical coordinates (latitude and longitude), elevation, and water surface level for each high-resolution cell are extracted to format the four vector columns. The same resampling procedure is completed for the low-resolution floodplain map to the produced resampled flood depth cells with the same resolution of the DEM. The downscaled flood depth is calculated through determining which cells experience overtopping through the following equation:

$$\text{Downscaled Flood Depth (m)} = \text{Water Surface Level} - \text{Land Elevation} \quad (1)$$

All downscaled cells with flood depths below zero are altered to zero. The cells containing a downscaled flood depth are classified as flooded cells, while the remaining are categorised as non-flooded cells. The following procedure results in a high-resolution floodplain map that presents depth in Figure 22, with the map presenting the downscaled flood depth (derived from equation 1) and a colour scale on the right.

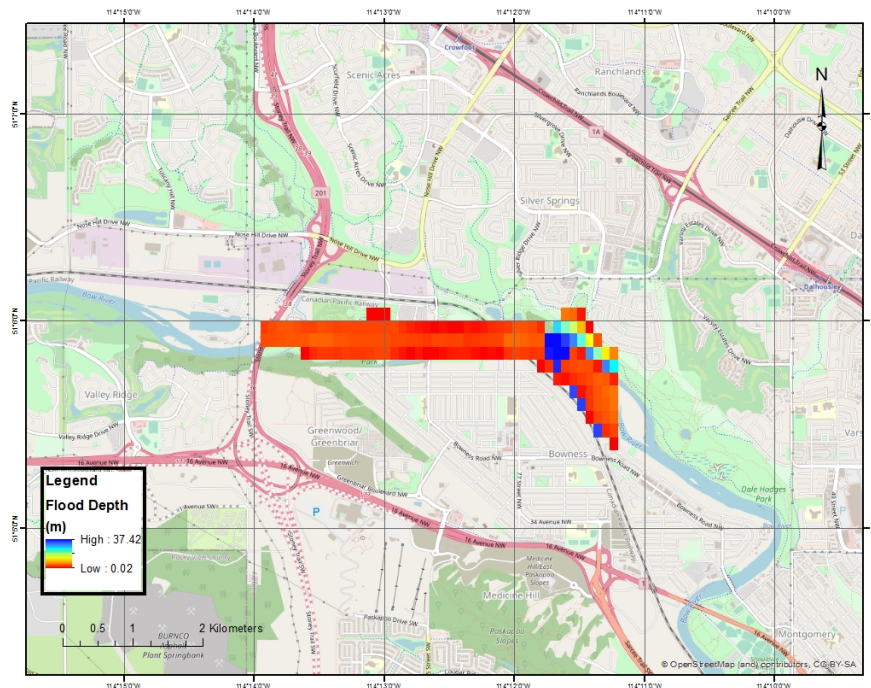


Figure 22: Downscaled floodplain map following equation 1 for the selected region



Extreme flood depths are produced due to the sensitivity of the DEM resolution compared to the low-resolution floodplain map, as seen in Figure 22, with extreme flood depths up to 38 m. This is due to the amount of high-resolution DEM cells and differentials in elevation points when compared to the low-resolution water surface level cells. To remove extreme flood depths, each high-resolution downscaled flood depth is constricted by the resampled flood depth cells from the low-resolution floodplain map. All cells with downscaled depths greater than the resampled water depths are identified as extreme flood depth cells and removed from the downscaled flood depths, which are then inputted with their coordinates into a 3D scattered interpolant. The scattered interpolant executes the nearest neighbour interpolation and extrapolation method for the extreme flood depth cells to transform the extreme flood depths to appropriate downscaled flood depths. The resulting downscaled flood depths generate the high-resolution floodplain map seen in Figure 23 which includes a colour scale.

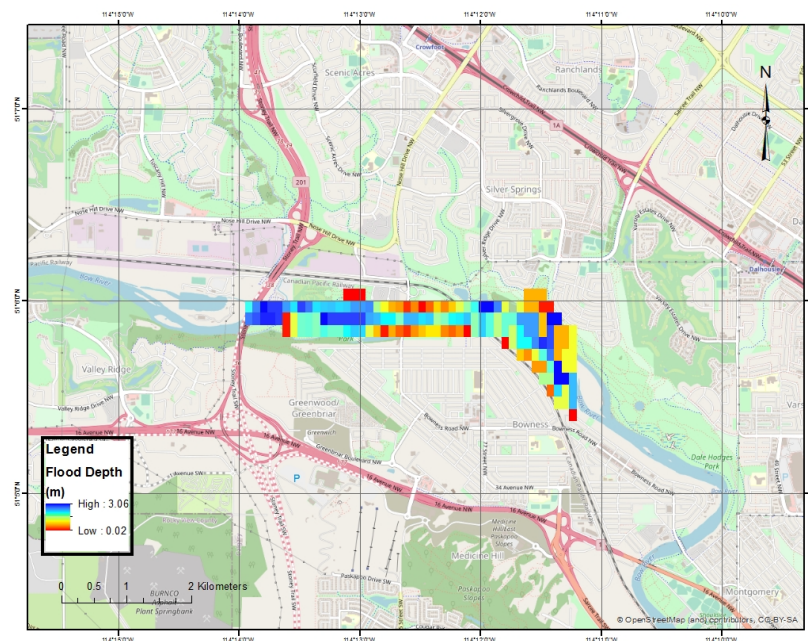


Figure 23: Downscaled flood depths following the water depth constricting the maximum flood depth for the selected region

Due to the first conflict of the downscaling methodology, explained in section 5.3.3, the approach to determine whether non-flooded cells adjacent to flooded cells can be flooded is determined. A water surface level map that covers the reduced DEM

is created through adding the downscaled flood depths to the elevation points. All adjacent cells are checked for flooding through the equation 2:

$$\text{Water Surface Level (adjacent flooded cell)} > \text{Elevation (nonflooded cell)} \quad (2)$$

When the flooding condition is met for any non-flooded cell, the cell becomes a flooded cell and the downscaled flood depth is calculated through equation 3.

$$\begin{aligned} &\text{Downscaled Water Depth (m)} \\ &= \text{Water Surface Level (adjacent flooded cell)} \\ &- \text{Elevation (nonflooded cell)} \quad (3) \end{aligned}$$

This generates an updated high-resolution floodplain map, depicted in Figure 24, along with a colour scale for the downscaled water depths.

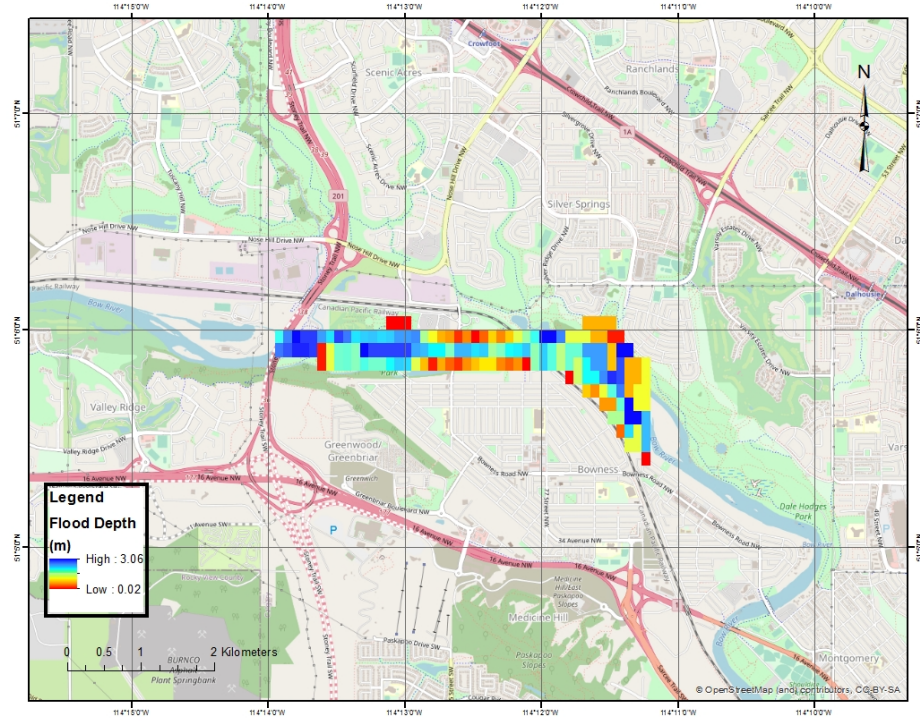


Figure 24: Downscaled flood depths following the adjacent flood cell condition in equation 3.

To ensure the downscaling methodology preserves the mass-conservation condition, a final post-processing approach is adopted, which guarantees the flooded volume from the low-resolution floodplain map is equal to that of the downscaled floodplain map. The flooded volume can be calculated through equation 4.

$$\text{Flooded Volume (m}^3\text{)} = \left( \sum \text{Flood Depths} \right) \times \text{Cell Area} \quad (4)$$

For the scenario where the downscaled flooded volume is lower than the low-resolution flooded volume, the downscaled flood depths are iteratively increased until the mass-conservation conditions are met. Consequently, the final high-resolution floodplain map is created, outlined in Figure 25 with a colour scale to present the varying downscaled flood depths across the selected region. As a result of the downscaling methodology, the number of flooded cells in the selected region have increased from 11 cells of 500 m spatial resolution to 164 cells of 100 m.

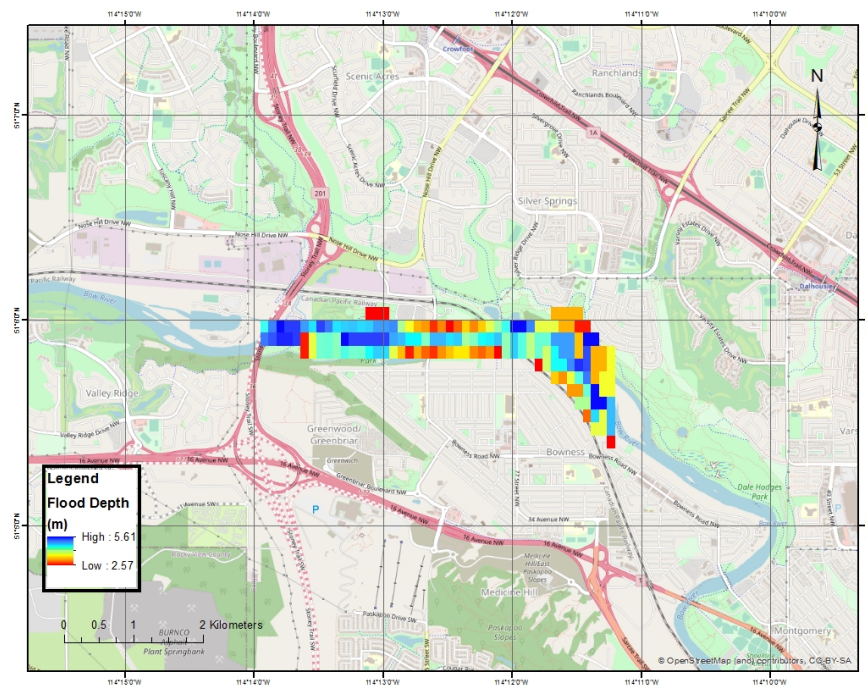


Figure 25: Final downscaled flood depths following the mass conservation step for the selected region with a colour scale.

## 6. Results and Discussion

Since the current resolution of the national floodplain map is inadequate for identifying local-scale flood risks, the downscaling methodology has been applied to the floodplain maps for the Calgary and New Brunswick case studies. The 100-year and 200-year floodplain maps produced within the national floodplain framework are used for each case study. The four maps are downscaled to produce eight maps of different spatial resolutions to test the downscaling sensitivity, performance, and capacity. The downscaled floodplain map spatial resolutions and their availability are detailed in Table 2.

Table 2: Summary of the location for each floodplain map and their respective spatial resolution

<b>Spatial Resolution (m)</b>	<b>Calgary Floodplain Maps (Appendix C)</b>		<b>New Brunswick Floodplain Maps (Appendix D)</b>	
	<b>100-year</b>	<b>200-year</b>	<b>100-year</b>	<b>200-year</b>
20	C1	C2	D1	D2
40	C3	C4	D3	D4
60	C5	C6	D5	D6
80	C7	C8	D7	D8
100	C9	C10	D9	D10
200	C11	C12	D11	D12
300	C13	C14	D13	D14
400	C15	C16	D15	D16

The results section is designed to assess the ability of the floodplain maps to identify local risks, the accuracy of the downscaling, and the computational time required to perform the downscaling. The downscaled floodplain maps are analysed to discuss the performance, limits, and ability of the methodology to be implemented for various resolutions. A volume conservation test is performed to analyse the accuracy of the methodology and its ability to ascertain mass-conservation conditions. Finally, a computational time study is completed to review the methodologies' abilities to downscale floodplain maps in a practical time period. By producing downscaled maps

at eight different spatial resolutions, the effectiveness of the downscaled spatial resolution within practical application of floodplain management techniques can be analysed. Additionally, the implementation of downscaling to eight spatial resolutions presents the overall ability and capacity of the downscaling methodology.

## **6.1 Spatial Resolutions**

Before discussing the results of the downscaling methodology, it is important to note the significance of the role spatial resolutions play on producing accurate terrain representations and identifying flood risk at local scales. As previously noted, the determining factor for the spatial resolution of the downscaled floodplain maps is the resolution of the inputted DEM. Eight different spatial resolutions were applied to the DEM to compare the sensitivities of the downscaling methodology in regard to the spatial resolution. Figure 26 presents the elevations of the eight different spatial resolutions along a cross section in the Bow and Elbow River Basin. The cross-section occupying the spatial resolution of 400 m is the one most noticeable in differentiating from the other cross-section due to its accuracy in representing the terrain data. The cross-section presents the terrain data with fewer elevation points with the distance due to its coarser resolution leading to an uneven cross-section for the elevation and an overall lower accuracy. Although the 200 m and 300 m resolutions illustrate an improved ability at representing the elevation points along the cross-section of the channel, the two resolutions fail to overlap with the finer resolutions in both the peaks and troughs along the cross-section. The remaining spatial resolutions present the best ability to represent the elevation conditions and obstructions for the presented cross-section. The impact of employing higher resolution terrain data allows for obstructions to be accounted for in local scales, improving the ability to implement the downscaled floodplain maps for cities and communities.

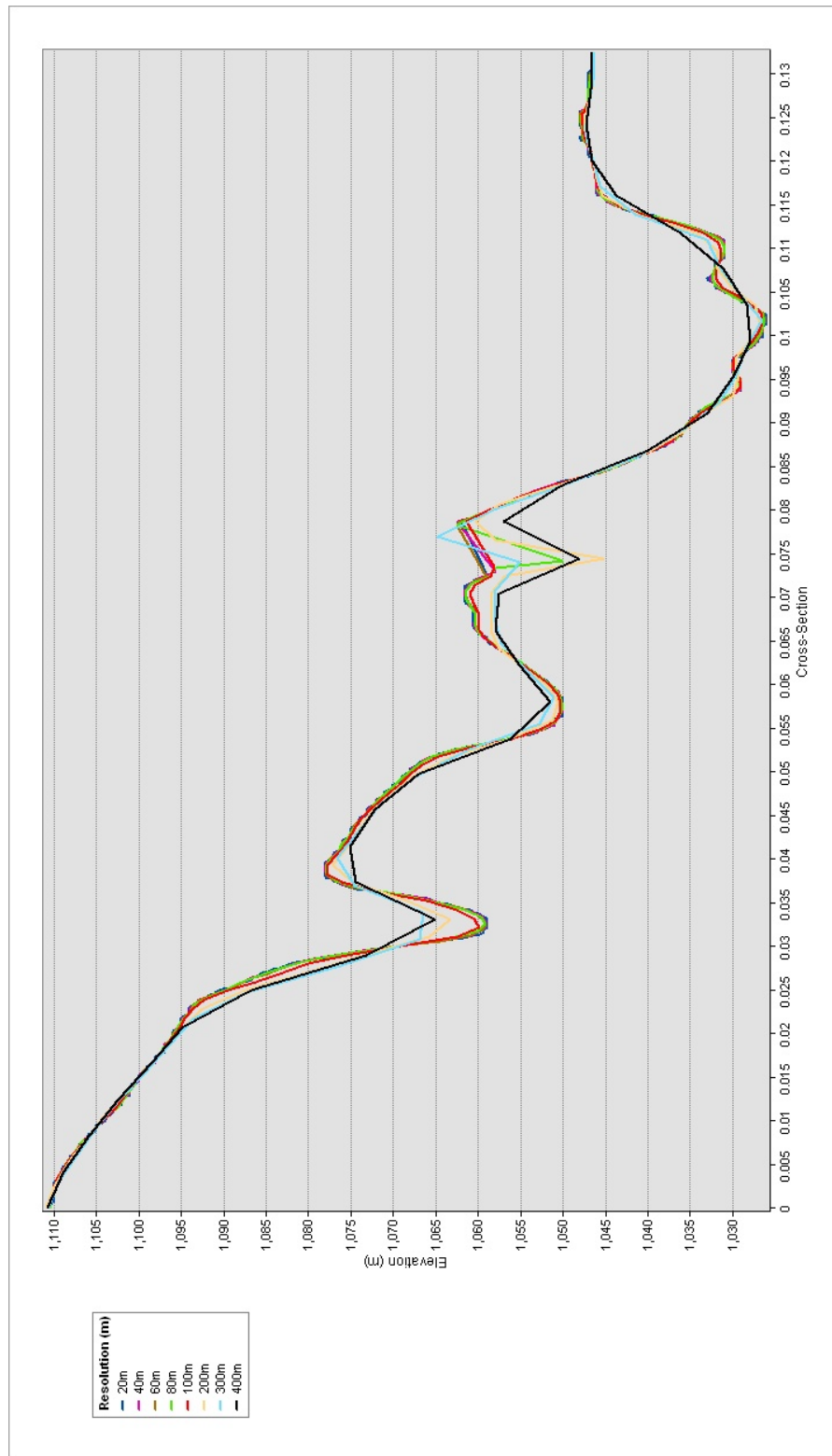


Figure 26: Cross-section comparison presenting elevation data for the different spatial resolutions

The impact of spatial resolution in mapping is further established through presenting a comparison of flood depth cells at three different spatial resolutions.



Figure 27 reveals the grid cell from one 500 m cell containing one flood depth consistent for the entirety of the cell (illustrated in red). Figure 28 presents the flood depth grid cells of 100 m resolution within the outline of the 500 m cell previously presented. The colours represent the varying flood depths across the 500 m cell area that previously consisted of a single flood depth. Figure 29 presents flood depth grid cells of 20 m within the outline of the original 500 m cell, with the colours representing the varying flood depth of the 20 m cells. The impact from downscaling and improving the final resolutions can be clearly visualised, as the 100 m spatial resolution increases the 1 elevation cell to 25 elevation cells, while the 20 m spatial resolution increases the 1 elevation cell to 576 cells. By increasing the resolution, the detail available in the floodplain maps will dramatically increase and become increasingly applicable to local-scale floodplain mapping.

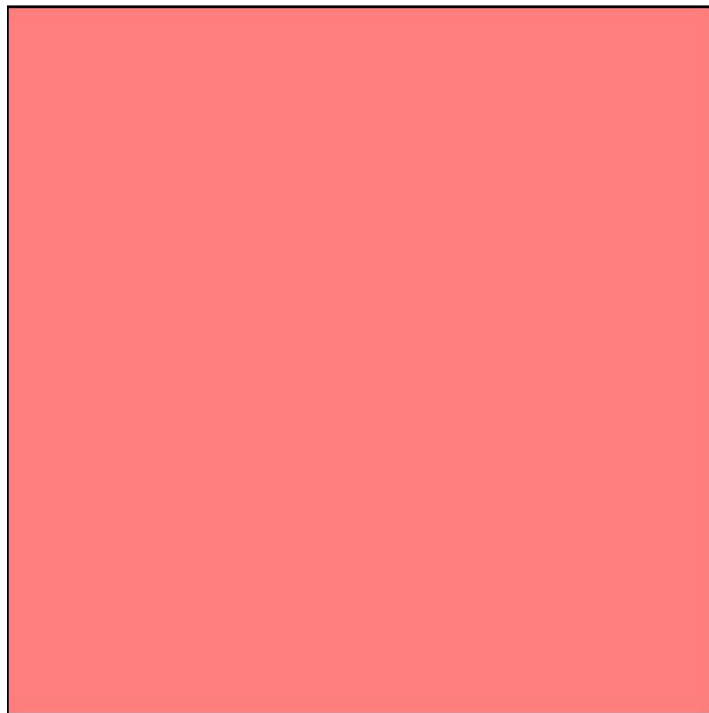


Figure 27: 500 m spatial resolution grid cell. The colour represents the single flood depth for the 500 m cell.

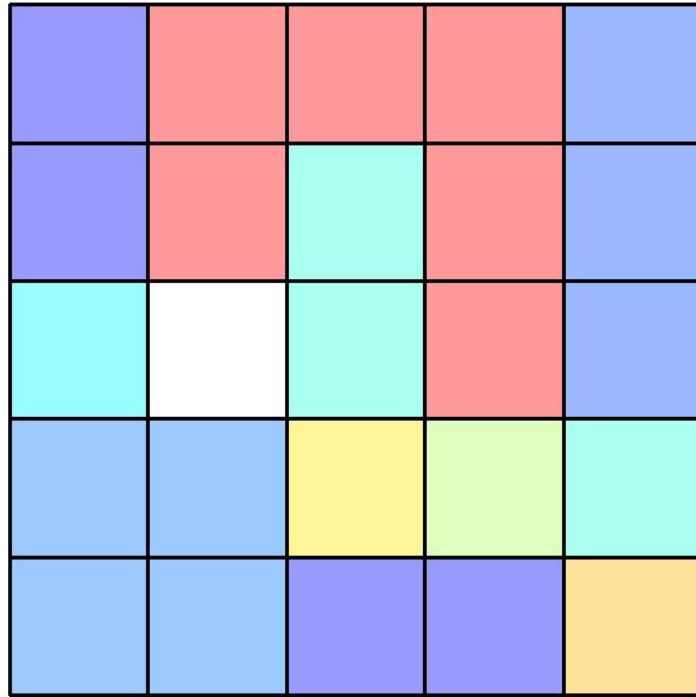


Figure 28: 100 m spatial resolution grid cells within one 500 m spatial resolution grid cell. The colours represent the flood depth for each 100m cell. Red Cells represent no flooding, while the remaining coloured cells represent flooded cells with varying depths. All white cells occupy no flood depth values.

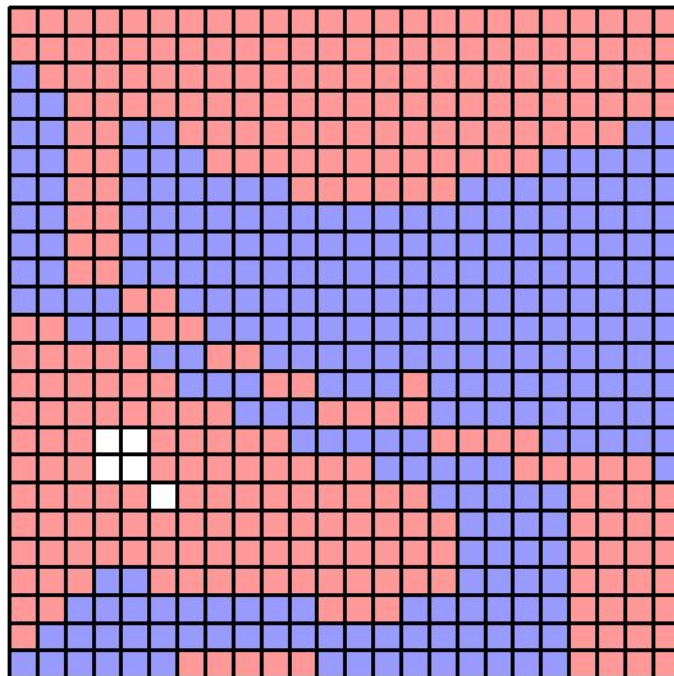


Figure 29: 20 m spatial resolution grid cells within one 500 m input spatial resolution grid cell. The colours represent the flood depth for each 20m cell. Red cells represent no flooding, while blue cells represent flooded cells. All white cells occupy no flood depth values.



## **6.2     Downscaled Floodplain Mapping**

The four low-resolution floodplain maps have each been downscaled to produce eight downscaled floodplain maps for the different resolutions for each low-resolution one. The low-resolution floodplain maps for the 100-year and 200-year flood events for Calgary can be seen in Figures 30 and 31, respectively, while the low-resolution floodplain maps for the 100-year and 200-year flood events for New Brunswick can be seen in Figures 32 and 33, respectively. The downscaled floodplain maps include eight spatial resolutions of 20, 40, 60, 80, 100, 200, 300, and 400 m. It is important to note that benchmark maps in Canada used to verify the flood extent accuracy are only available for floodplain maps with spatial resolutions of 1 km. Upscaling the floodplain maps can present performance statistics for the flood extent, however, the Mohanty and Simonovic study (2020a) has already demonstrated the accuracy of the national floodplain maps. This section includes a discussion on the performance of the downscaling methodology with regard to the derived floodplain maps.

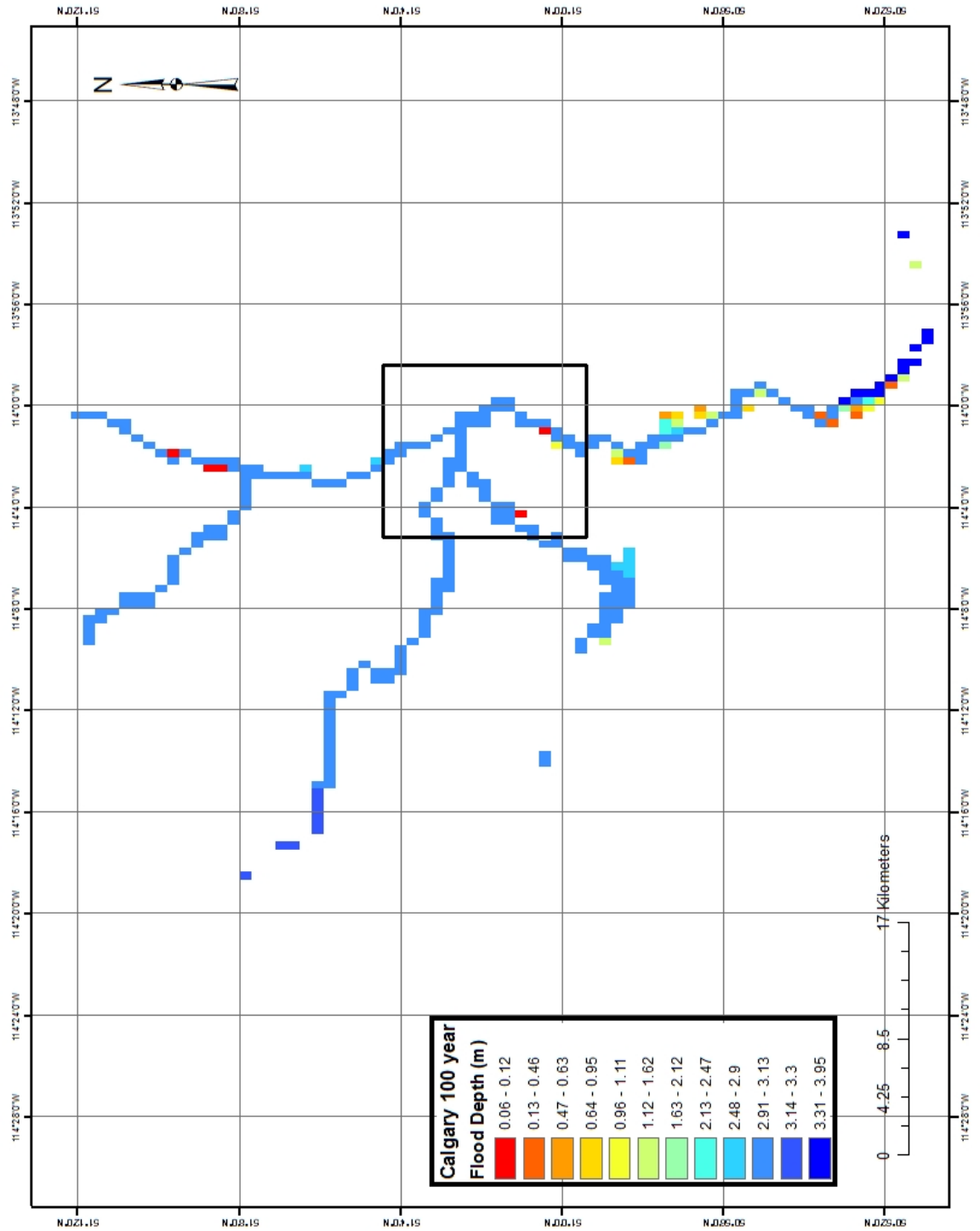


Figure 30: 100-year low-resolution floodplain map for Calgary

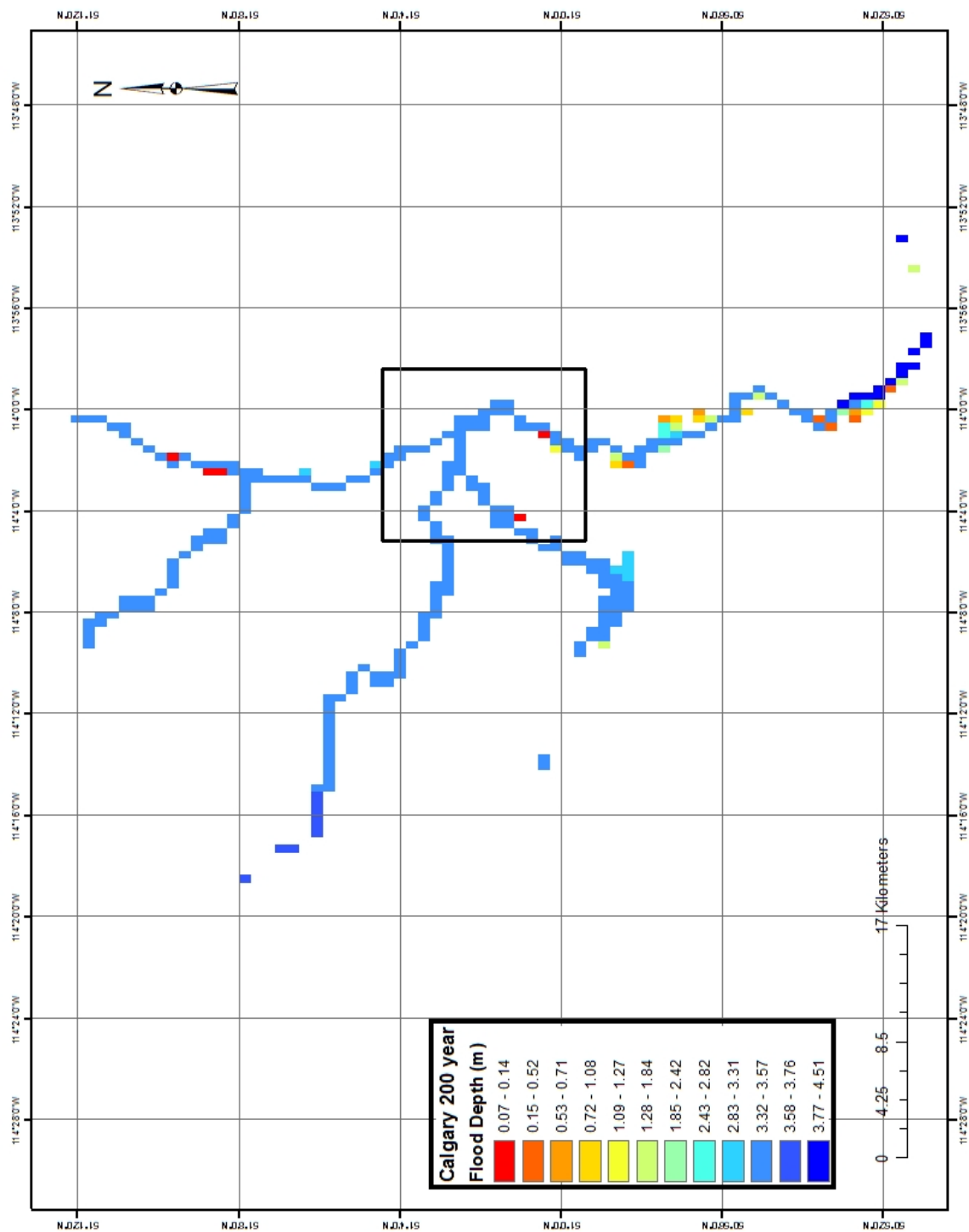


Figure 31: 200-year low-resolution floodplain map for Calgary

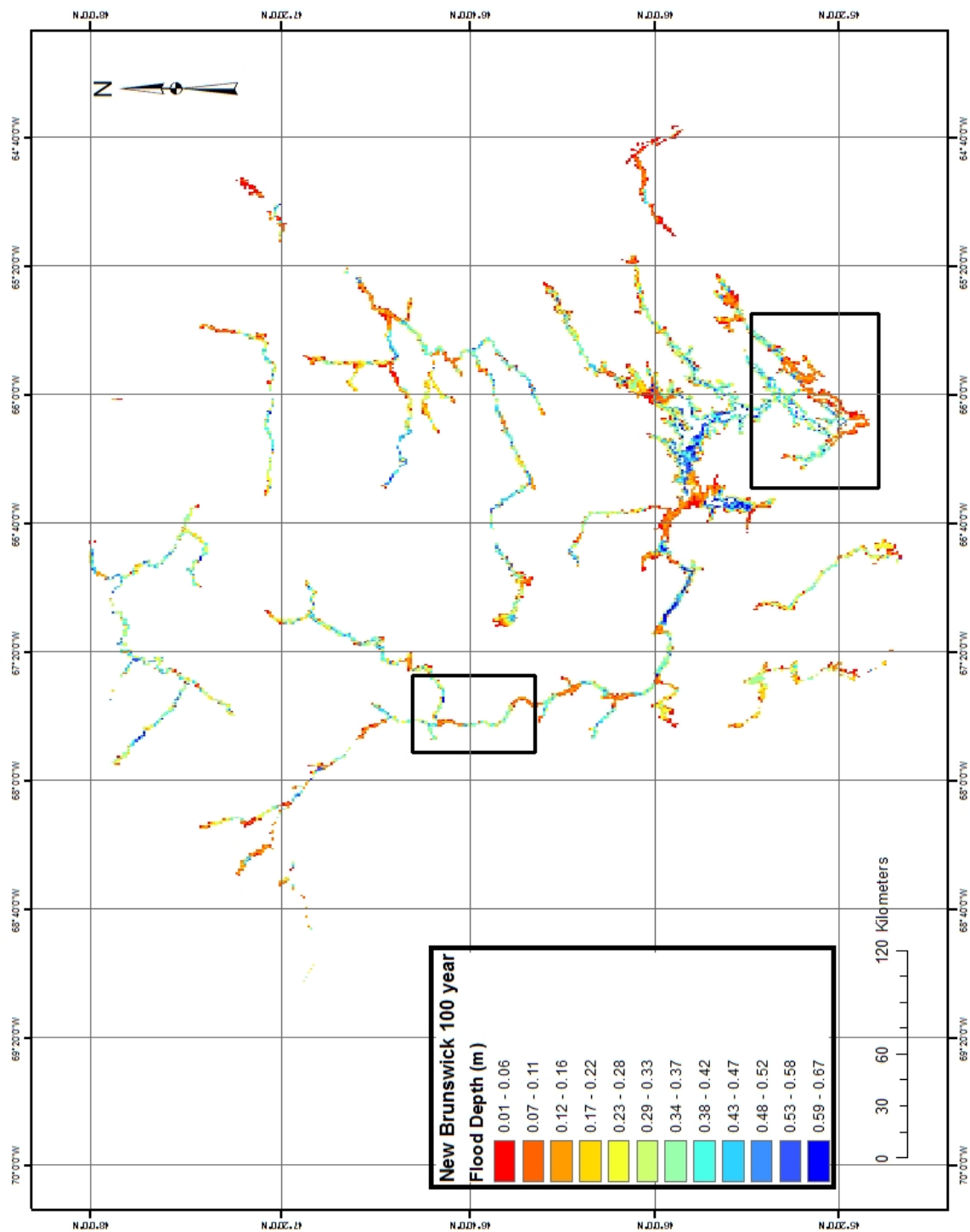


Figure 32: 100-year low-resolution floodplain map for New Brunswick

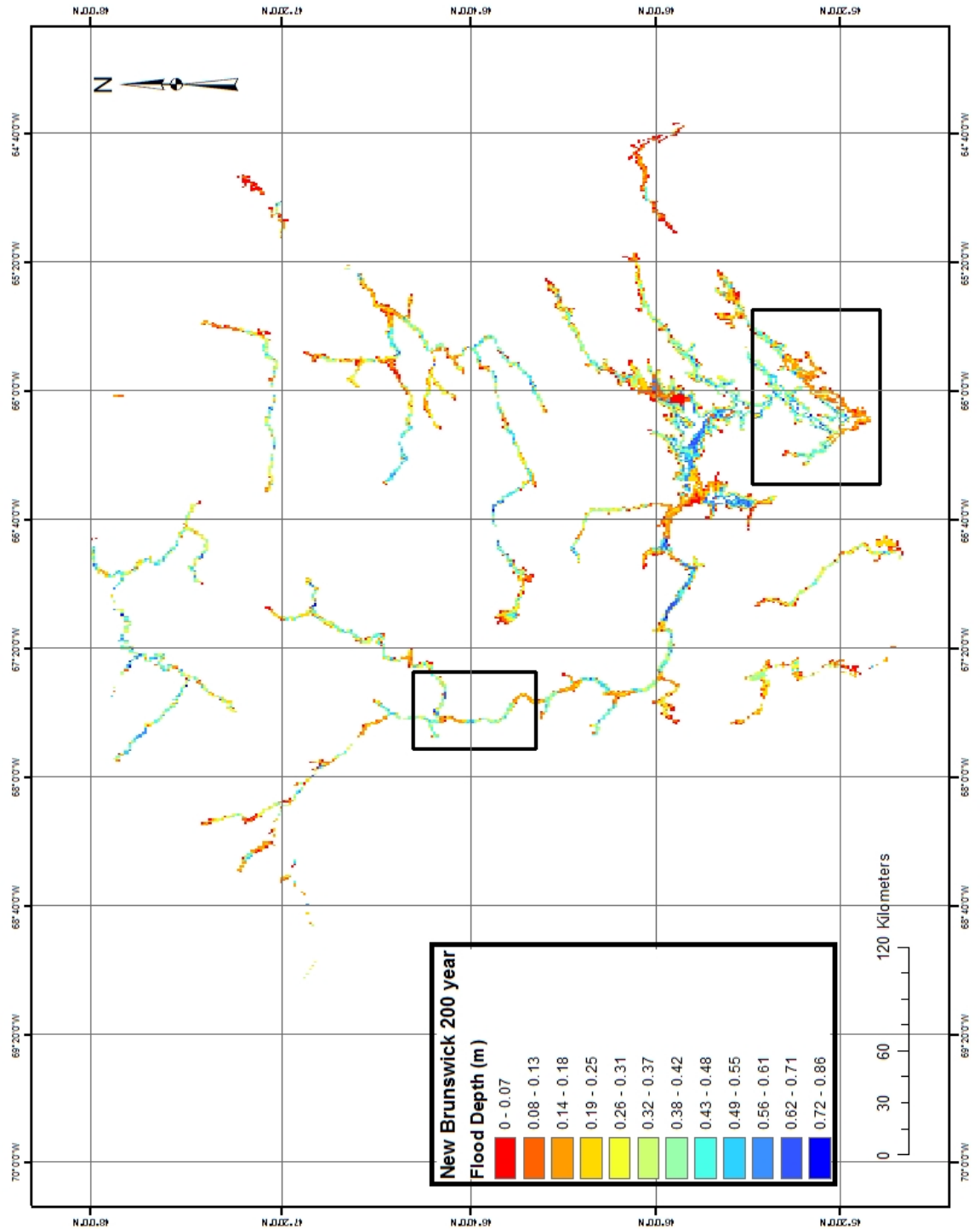


Figure 33: 200-year low-resolution floodplain map for New Brunswick

### 6.2.1 Calgary Case Study Results

The first two downscaled maps analysed for Calgary are the 100-year and 200-year return period floodplain maps at 100 m spatial resolution, presented in Figures 34

and 35, respectively. They include a basemap to display how effective the downscaling methodology follows the rivers' nuances. The purpose of focusing the discussion on the 100 m resolution maps is due to the following two reasons. First, there are limited improvements for calculating the accuracy of the boundary of the flooded extents when improving the resolution of the floodplain maps beyond 100 m (Schumann et al., 2013a). Second, the large region floodplain maps produced within the Fathom-Global study were further produced at 90 m resolutions due to the ability of the resolution to represent local detailed data (Sampson et al., 2015).

The first improvement observed in the downscaled floodplain maps at 100 m resolution is the improved boundary of the flooded extent. Prior to downscaling, the low-resolution floodplain map cells poorly represented the boundaries of the flooded area due to their coarse cell size. However, with the downscaling methodology, the 100 m resolution maps depict a more accurate representation for the boundaries of the flooded area by incorporating a greater number of cells that can be defined as flooded or non-flooded through overtopping calculations. The improved boundary allows the floodplain maps to be applied within local scale studies as it enhances the definition of the flooded and non-flooded areas. The second improvement is the ability of the floodplain maps to better represent flood depths for local-scale regions. As discussed in chapter 6.1, the increase in resolution allows for a greater number of cells within the same area to receive individualised flood depths. These two improvements will allow individual properties and infrastructure exposed in the flooded area to have a more defined flood depth. Flood proofing measures and development restrictions can be further applied to prevent the local risk of flooding. The third improvement is the ability of the flooded cells to more precisely follow the nuances of the rivers compared to that of the low-resolution map. Within the low-resolution map, the cells poorly overlay many regions of the river where flooding is expected to occur. By incorporating a high-resolution DEM, the elevation data represents the case study region in a much more detailed manner and can better project regions that will experience flooding.

Figures 36 and 38 illustrate the confluence for the Bow and Elbow Rivers, highlighted in Figures 34 and 35, respectively, in the 100-year and 200-year return period floodplain maps at 100 m spatial resolution. The impact of the increased spatial

resolution can be seen when compared to the confluence region from the low-resolution maps in Figures 37 and 38. The increase of spatial resolution provides a better representation of the streets and properties that would be flooded during the two return period flooding events when compared to that of the low-resolution map. Projected flood depths can be assigned more accurately to the individual infrastructure located in the flooded area. The two improvements allow the ability to produce local-scale flood studies to decide on flood proofing measures for infrastructure and zonal restrictions for development.

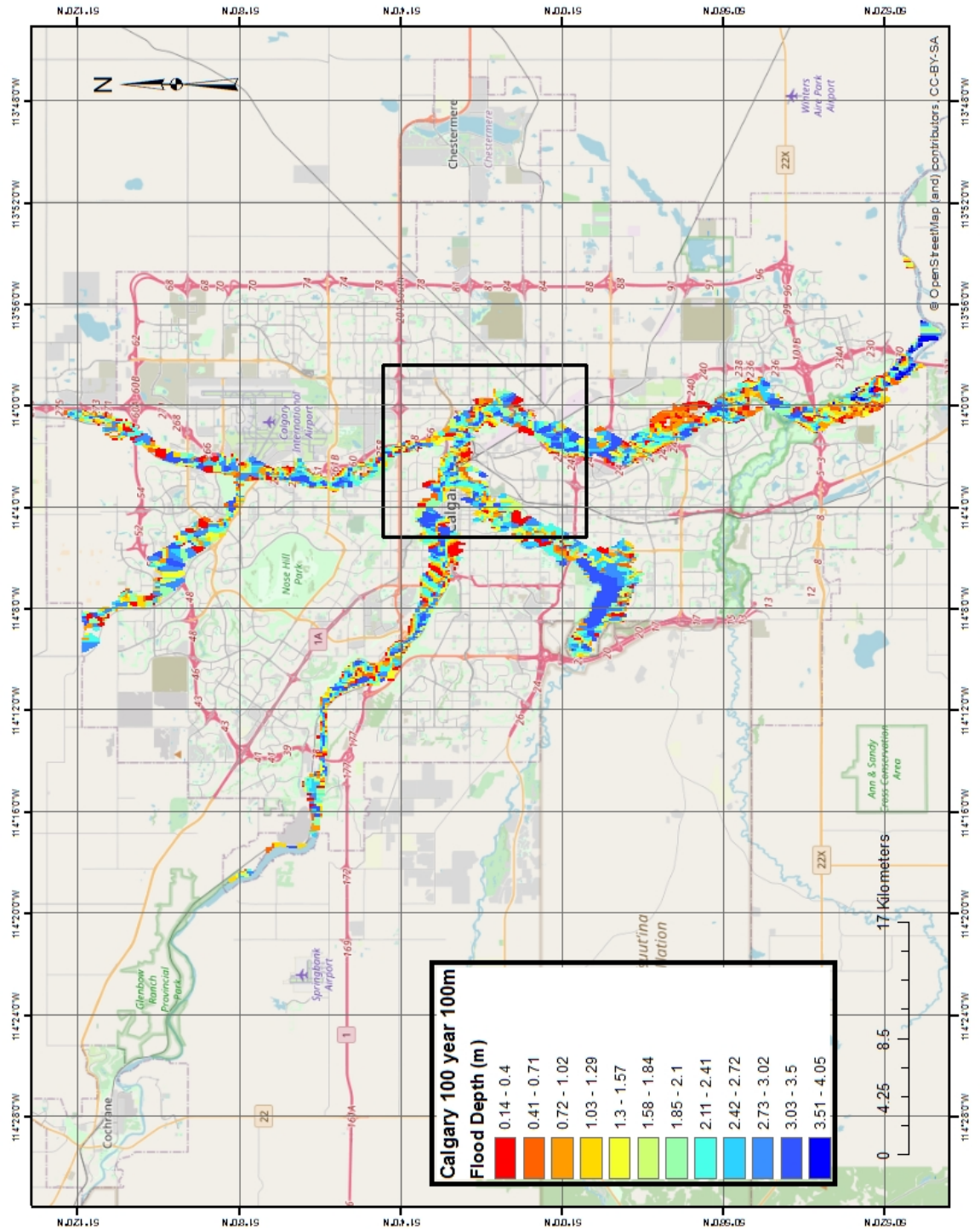


Figure 34: Downscaled 100m resolution floodplain for Calgary 100-year flood



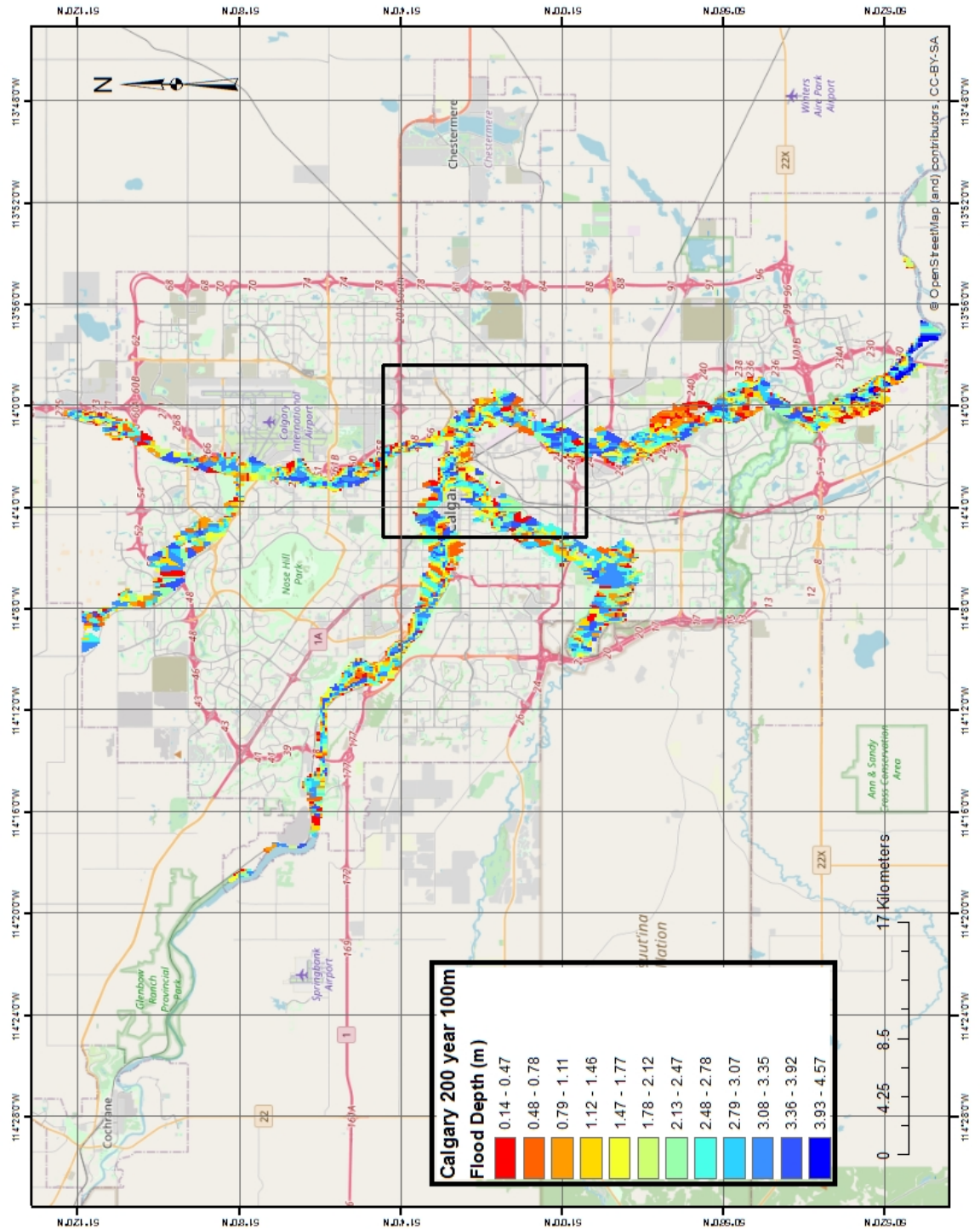


Figure 35: Downscaled 100m resolution floodplain map for Calgary 200-year flood

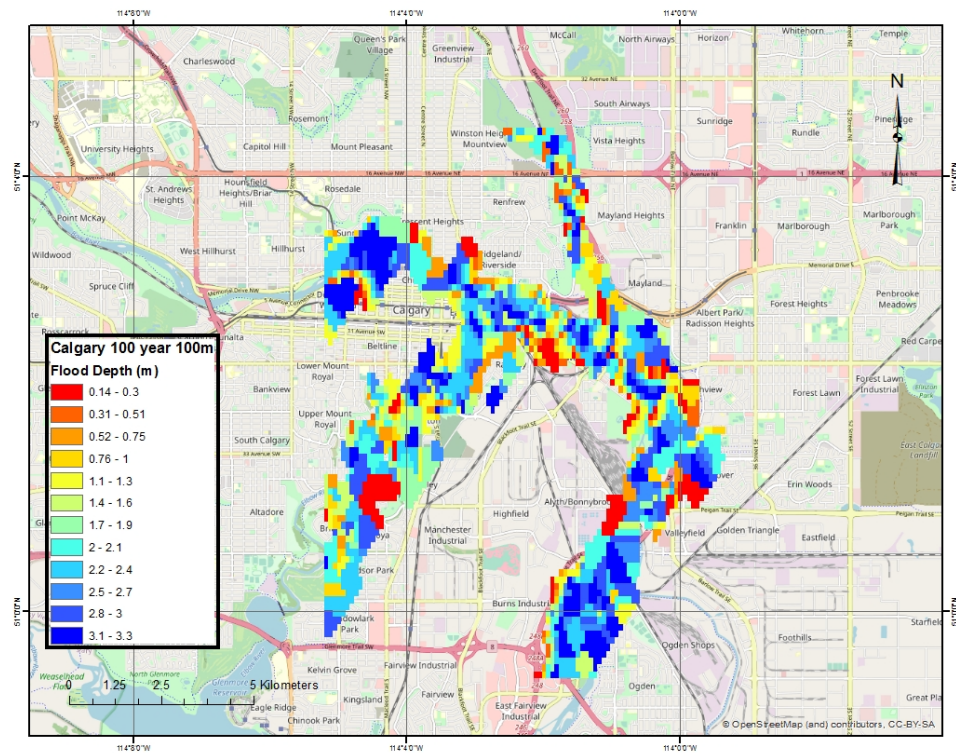


Figure 36: Downscaled 100m resolution floodplain map for Calgary 100-year flood presenting the confluence of the Bow and Elbow Rivers

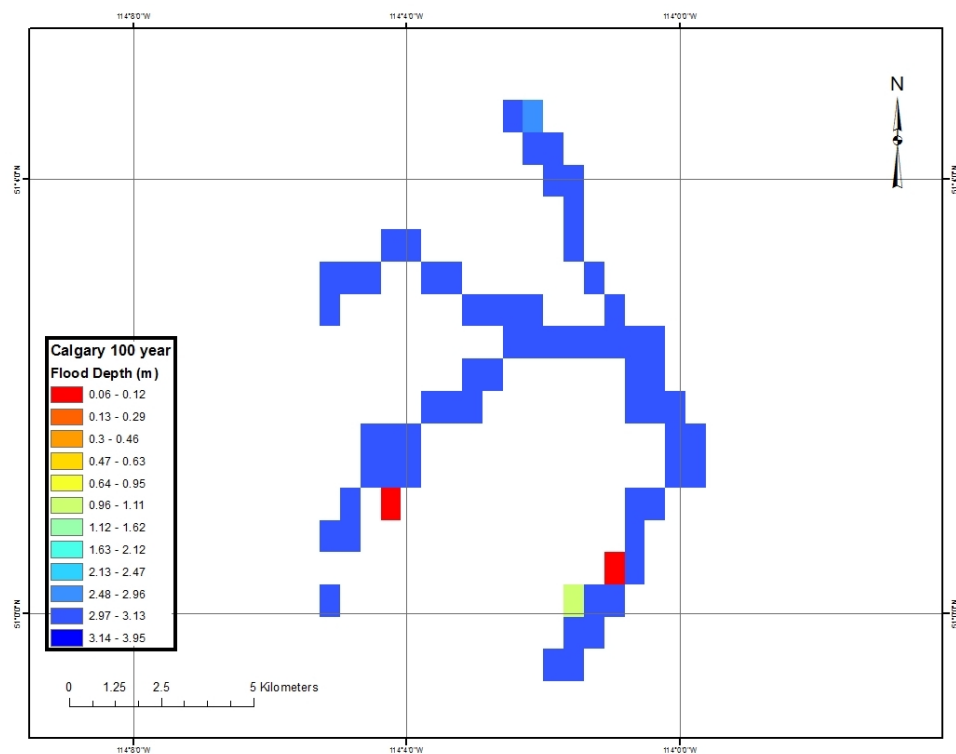


Figure 37: Low-resolution floodplain map for Calgary 100-year flood presenting the confluence of the Bow and Elbow Rivers

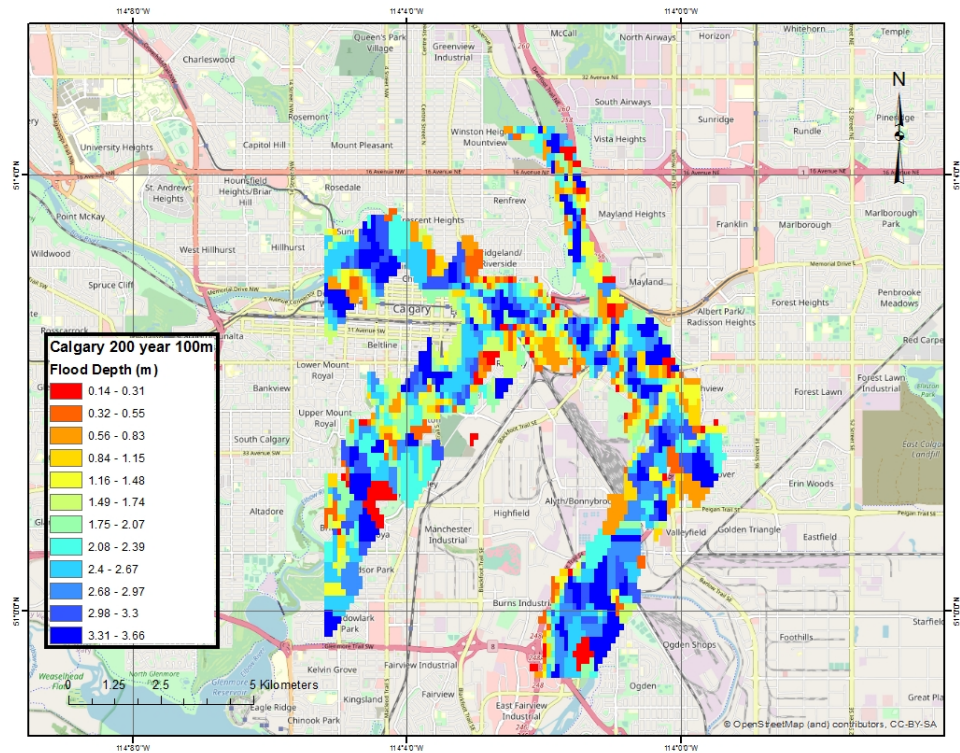


Figure 38: Downscaled 100m resolution floodplain map for Calgary 200-year flood presenting the confluence of the Bow and Elbow Rivers

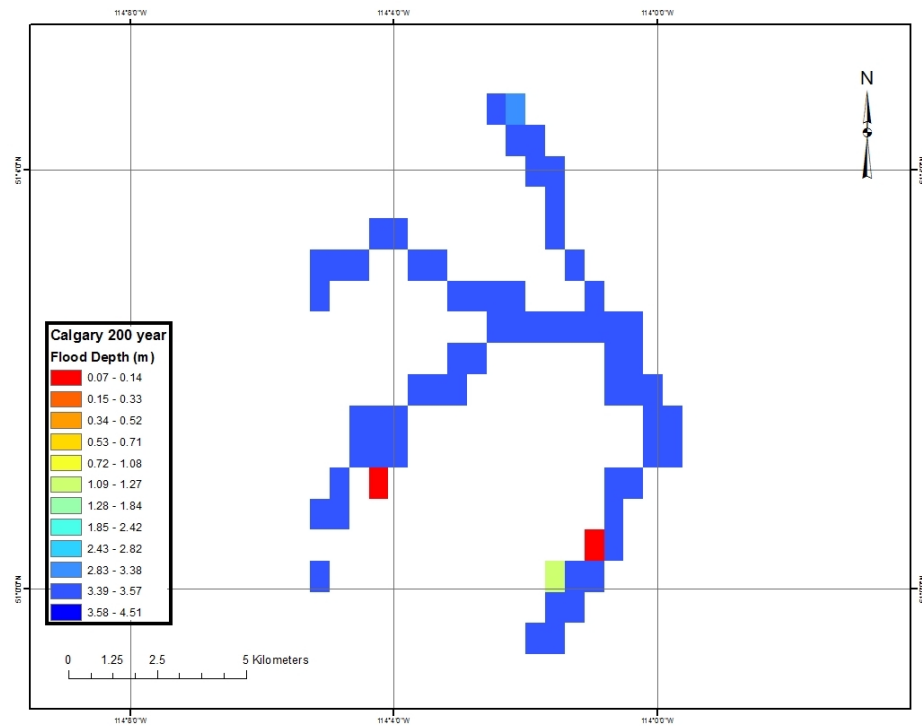


Figure 39: Low-resolution floodplain map for Calgary 200-year flood presenting the confluence of the Bow and Elbow Rivers

The remaining spatial resolution floodplain maps are available in Appendix C and encompass the highlighted confluence region. While the 20 m resolution maps present an increased spatial resolution, the enhancement of the flooded area's boundary is similar to that of the 100 m map. This further supports the note regarding limited improvements for the flooded boundary when improving spatial resolutions beyond 100 m. Furthermore, the 20 m resolution maps present irregular flood depths when contained within the previous low-resolution cell. This is due to increasing the resolution beyond the capabilities of the downscaling methodology. The enhancement of the flood boundary and the number of cells available for flood depths decrease beyond the 100 m resolution maps for the 200, 300, and 400 m resolution maps, further confirming the 100 m resolution maps as the appropriate choice for local-scale studies.

### ***6.2.2 New Brunswick Case Study Results***

As in the Calgary case, the two downscaled maps analysed further for the New Brunswick case study are the 100 m spatial resolution maps for the 100-year and 200-year return periods, presented in Figure 40 and Figure 41, respectively. The resolution improvements provide the ability for the maps to present local scale flooding conditions, due to the availability therein of enhanced flood boundaries and individualised flood depths for property and infrastructure. Improvements have been made in associating flood depths to local scale properties and infrastructure. This enables easier identification of local flood risks and utilisation of the floodplain maps for instituting flood proofing measures and development restrictions. The downscaled maps provide improvements within the flooded cells by following the rivers' nuances to a greater degree. This increases the likelihood of the cells as projected actually experiencing flooding conditions, as higher elevation features are incorporated to represent the river characteristics.

Figure 42 presents region A in the downscaled 100-year return period floodplain map compared to region A in the low-resolution floodplain map in Figure 43. The ability of downscaling to effectively enhance the boundary of the flooded area is further highlighted in the comparative resolution improvements in the two figures.

Enhancing the flooded boundary allows flood risks properties and infrastructure to be more accurately identified and to increase the possibility of downscaling being used in local scale studies. Region A in the downscale map also presents the improvements in spreading the flooded volume to regions outside the low-resolution cells. This is done through incorporating high resolution elevation data that accounts for identifying flood prone regions which previously were not expected to be flooded. Figure 44 presents region B in the downscaled 100-year return period map, compared to that of the lower-resolution map in Figure 45. The downscaled map continues to present the ability to identify both the boundary and the property exposure of the flooded area, unlike the low-resolution map.

One of the limitations that is revealed from analysing the New Brunswick downscaled maps is the inability of the downscaling methodology to make up for discontinuities in the low-resolution floodplain map. While discontinuities do not occur frequently, streams and reaches of the river network in New Brunswick are presented as not showing continuous flooding where flooding is expected to occur. This can lead to the national floodplain maps failing to account for flood prone regions and may require further local scale mapping.



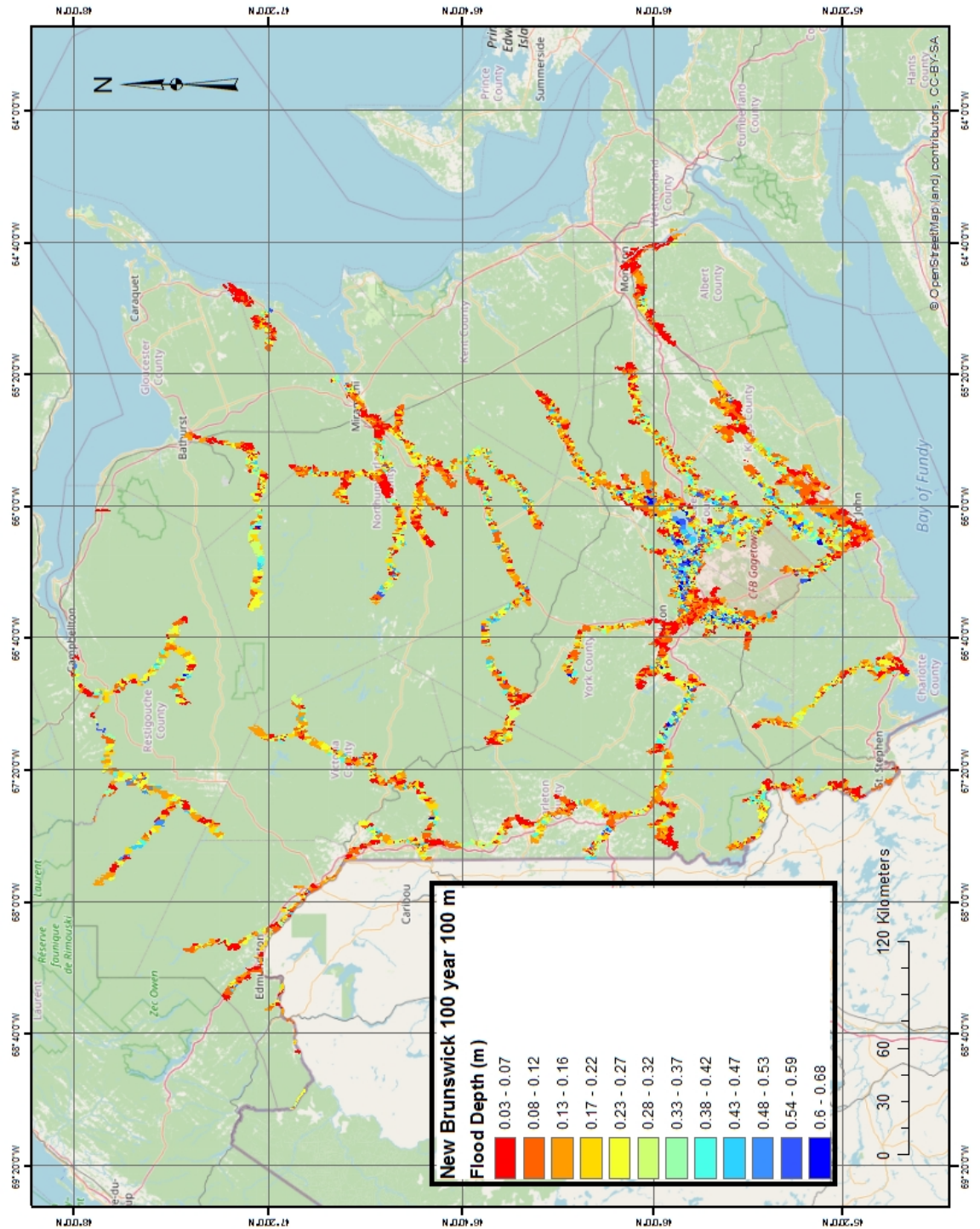


Figure 40: Downscaled 100 m resolution floodplain map for New Brunswick 100-year flood

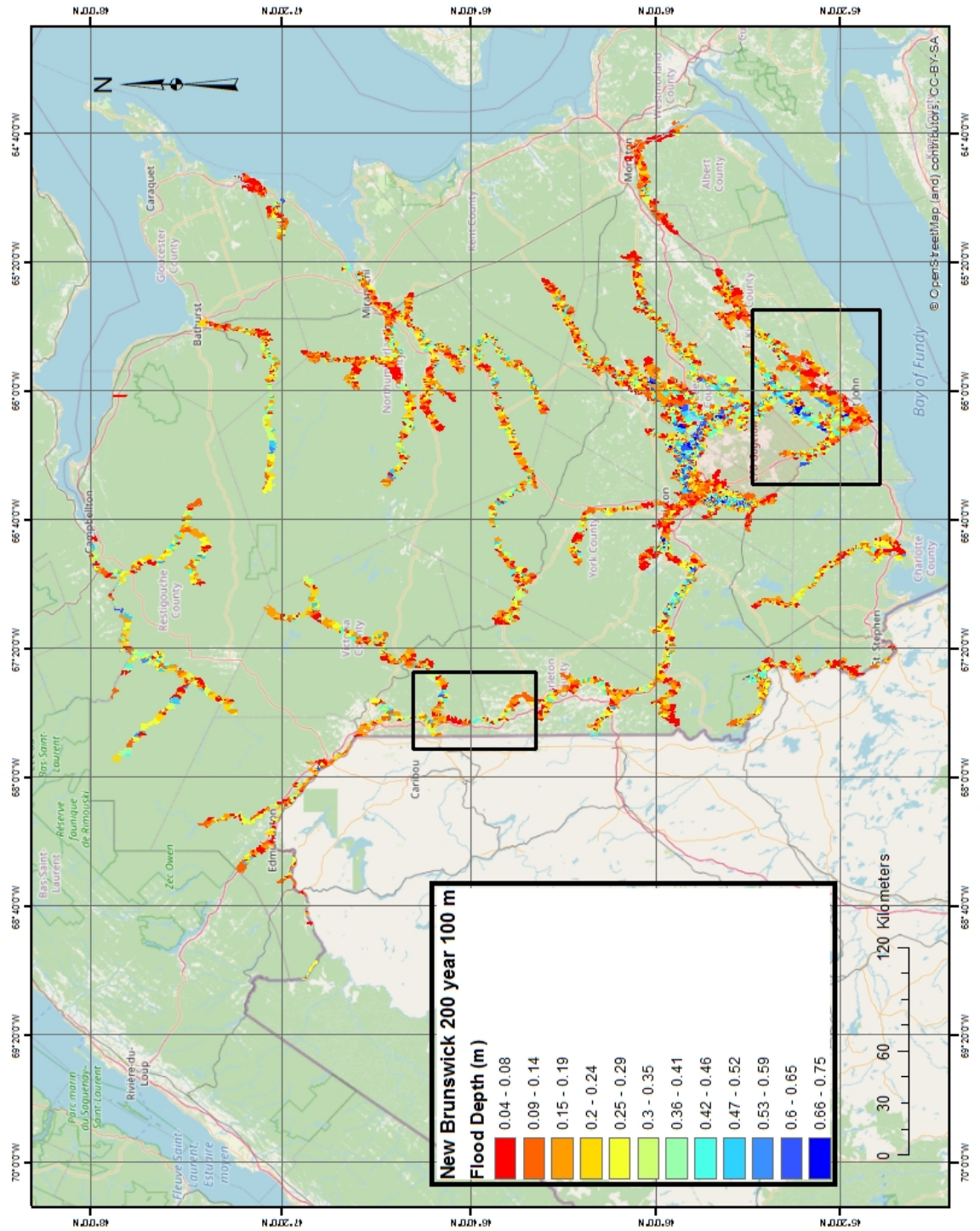


Figure 41: Downscaled 100 m resolution floodplain map for New Brunswick 200-year flood

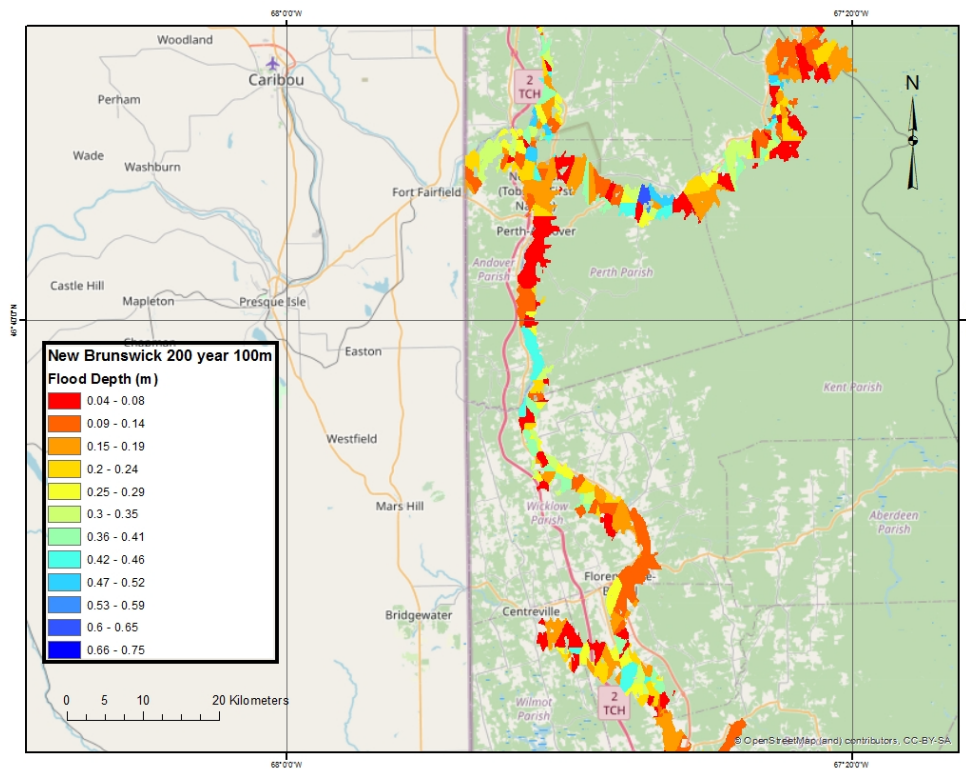


Figure 42: Region A downscaled 100 m resolution floodplain map for New Brunswick 100-year flood

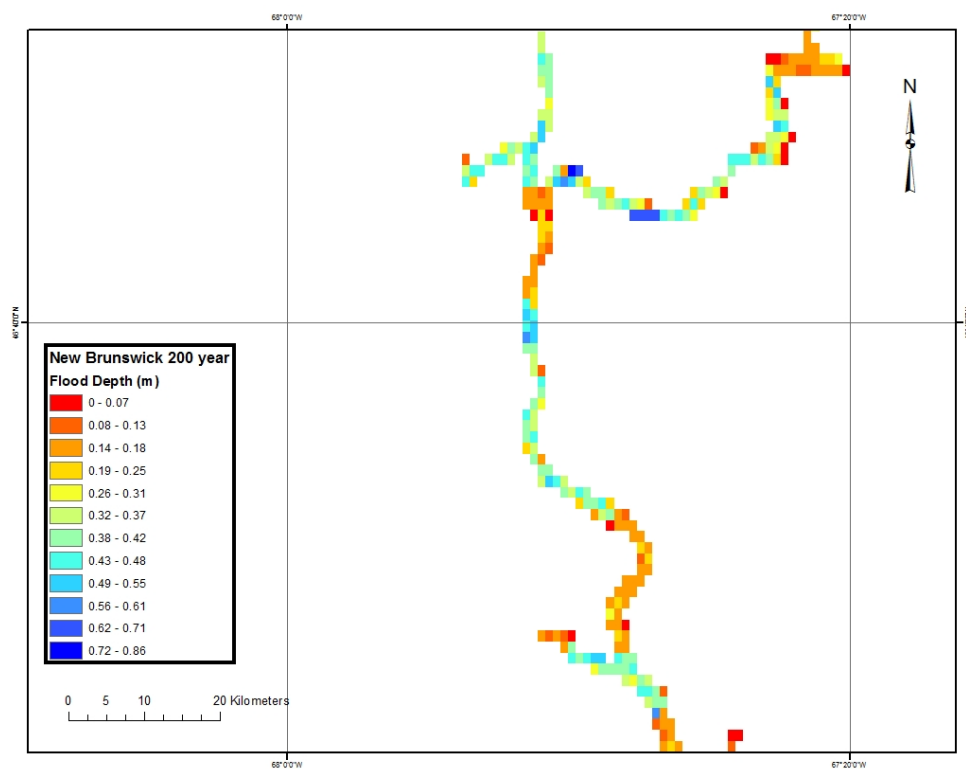


Figure 43: Region A low-resolution floodplain map for New Brunswick 100-year flood



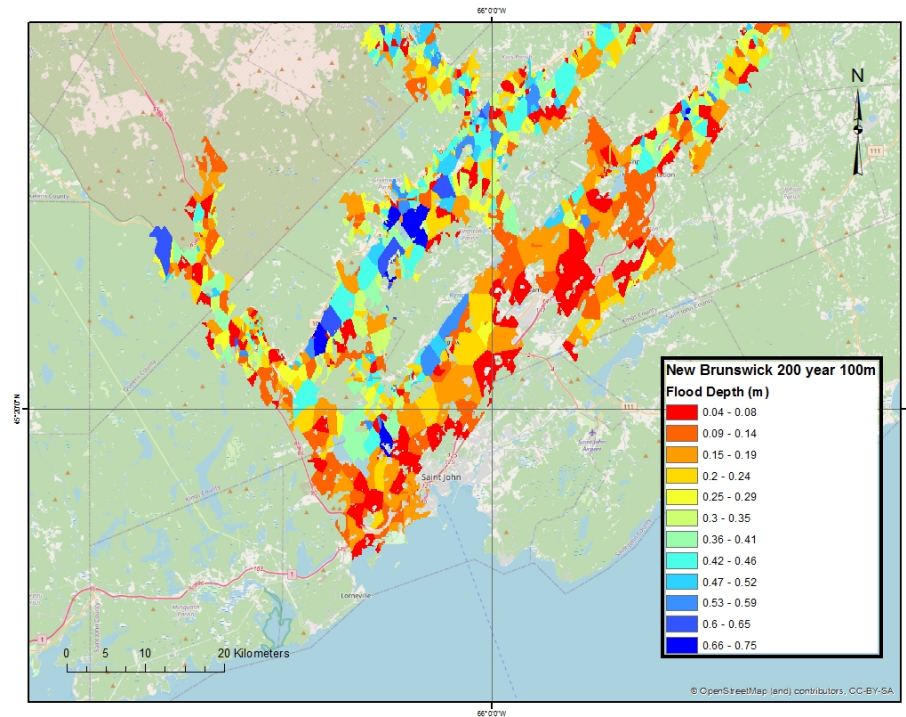


Figure 44: Region B downscaled 100 m resolution floodplain map for New Brunswick 100-year flood

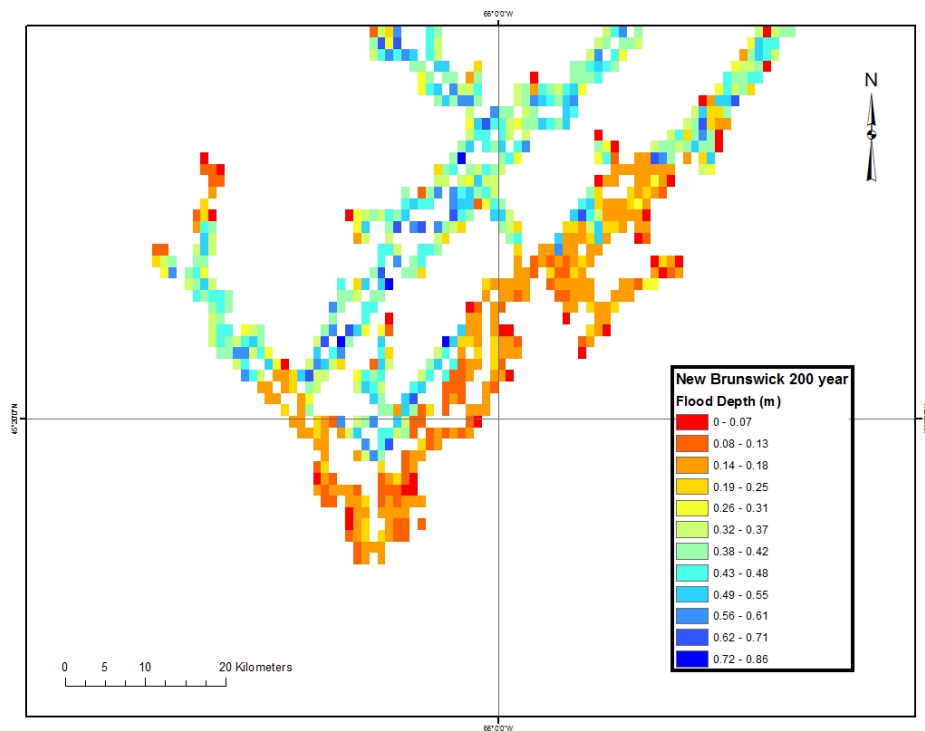


Figure 45: Region B low-resolution floodplain map for New Brunswick 100-year flood

The remaining spatial resolution floodplain maps for New Brunswick can be found in Appendix D, with regions A and B presented to local scales. For the 20 m

resolution maps, limited improvements are seen in the enhancement of the boundary when compared to the 100 m resolution maps. Additionally, the maps present limited increases for improving the flood depths when compared to the 100-m resolution maps. This is due to the limitations in the downscaling methodology with regard to improving the maps' spatial resolution to margins that are too fine. Resolution improvements in the 200, 300, and 400 m maps present less enhanced flood boundaries and the downscaled flood depths are less representable to local scale conditions.

### 6.3 Conservation of Flood Volume Analysis

As a result of the flooded volume of water for both return periods having been derived through the CaMa-Flood Hydrodynamic modelling process, the downscaling process should retain mass conservation conditions, where the flooded volume of water from the downscaled map is equal to that of the low-resolution map. A post-processing step has been performed to ensure the downscaling methodology retains mass conservation conditions; however, a volume conservation test has been completed following the initial downscaling and the first post-processing step to identify the accuracy and improvements of the overall downscaling approach. One important aspect to note when analysing the volume conservation results is the difference in spatial resolution of the Calgary and New Brunswick low-resolution maps undergoing downscaling. This characteristic of the inputted model will impact the overall ability to downscale the map to finer margins. With many GFM's producing floodplain maps with spatial resolution of approximately 1 km, it is of vital importance to implement the downscaling methodology with a floodplain map with spatial resolution of 1 km, as done with the New Brunswick case study.

Volume conservation has been calculated through Equation 5.

$$Volume\ Conserved\ (\%) = 100 \times \left( 1 - \frac{Volume_{pre} - Volume_{post}}{Volume_{post}} \right) \quad (5)$$

where  $Volume_{post}$  represents the volume of flood water after downscaling and  $Volume_{pre}$  represents the volume of flood water within the low-resolution floodplain

map. The total volume of flooded water is calculated by multiplying the total sum of flood depths by the cell size for each respective map.

The accuracy of volume conservation was first measured for the floodplain downscaling methodology in Subsection 5.3.2. Due to limiting the water surface elevation to their respective water surface elevation occupied by the low-resolution cell, the majority of volume estimates for the downscaled maps were less than that of the low-resolution map. Table 3 and Figure 46 present the volume conserved for the downscaled maps with their respective spatial resolution, location, and return period following the downscaling methodology.

Table 3: Volume conservation estimates for the downscaled floodplain maps following the downscaling methodology

<b>Resolution of Downscaled Floodplain Map (m)</b>	<b>Calgary</b>		<b>New Brunswick</b>	
	<b>100-Year Volume Conserved (%)</b>	<b>200-Year Volume Conserved (%)</b>	<b>100-Year Volume Conserved (%)</b>	<b>200-Year Volume Conserved (%)</b>
20	101	85	117	116
40	97	92	86	87
60	93	92	79	76
80	91	89	76	73
100	87	89	77	75
200	81	84	80	76
300	75	83	86	84
400	74	82	86	79

Depending on the case study area and return period, the maps deviate slightly in the relationship they present when downscaled, with regard to their spatial resolution versus the volume conserved. When downscaling to 20 m, the lone map that presents a volume estimation less than that of its pre-downscaled low-resolution volume is that of the 200-year return period for Calgary. This is primarily due to

issues with the methodology when downscaling to spatial resolutions that are too fine. The suggestion that overestimation occurs when downscaling to fine resolutions is exemplified in the New Brunswick return period case studies, as the volume conservation estimates drop between the spatial resolutions of 20 m and 80 m before improving for the lower resolutions following. On the other hand, volume estimates for Calgary continue to decrease with lower spatial resolutions, suggesting that the preliminary downscaling methodology is more effective when downscaling to higher resolutions.

Although volume conservation estimates for each spatial resolution all have an average greater than 80%, the estimations present the need for the further post-processing steps due to low estimates of 76% and 73% presented for the 80-m spatial resolution New Brunswick 100- and 200-year maps. To improve the accuracy of the downscaling methodology, the flooded volume estimations are required to increase and improve the percentage of volume conserved. Through identifying a solution to the first conflict of the downscaling methodology, as presented in Subsection 5.3.3, the accuracy of the downscaling methodology can be improved.

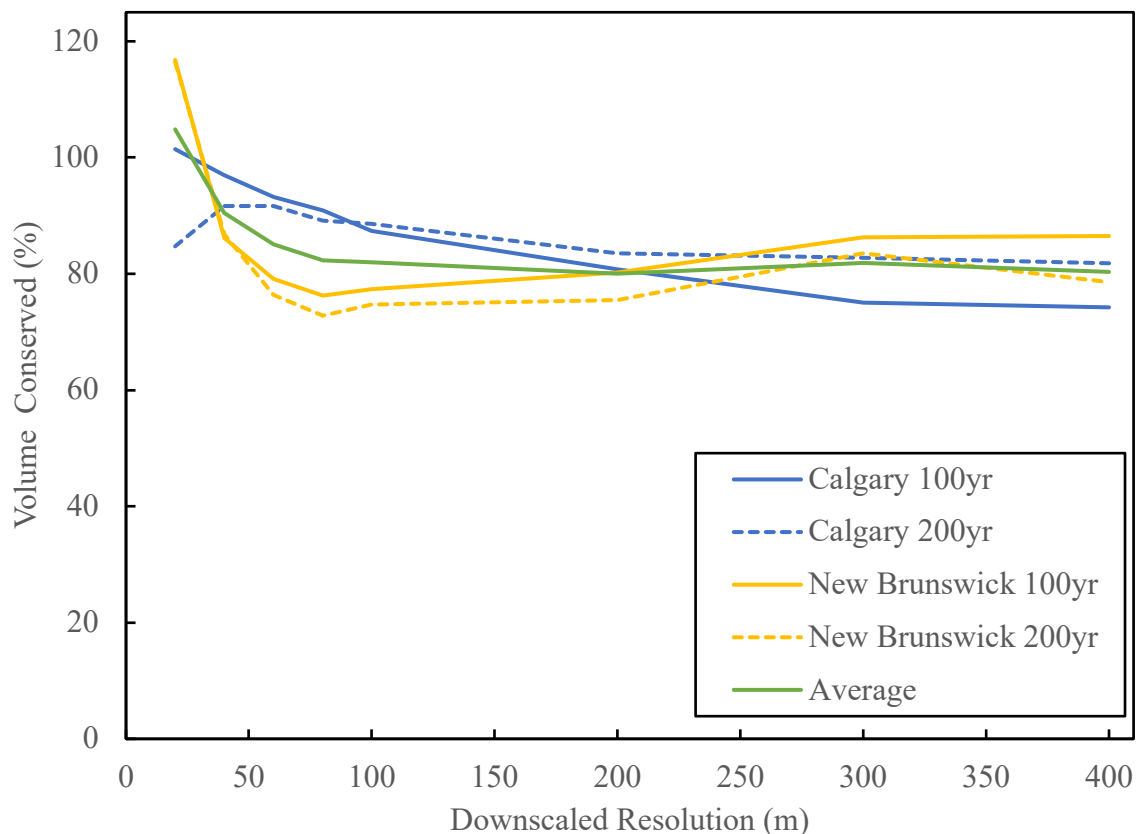


Figure 46: Volume conservation for downscaling methodology

The percentage for volume conservation was measured again following the post-processing technique of accounting for identifying flooded cells originally declared non-flooded due to their existing outside the low-resolution map region. Due to incorporating new flooded cells in the downscaled map, the flooded volume sees an increase and further improves the overall volume conservation of the downscaling approach. Table 4 and Figure 47 present the improved volume conservation estimates following the additional downscaling step.

Volume overestimation happened again in the 20 m spatial resolution maps for the 100-year return period in Calgary, and for both the 100- and 200-year return periods in New Brunswick. The two New Brunswick maps at 20 m resolution present the potential for overestimates occurring until the spatial resolution of 80 m, where volume conservation improves from lows of 80% and 77% at a resolution of 80m to 97% and 90% at a resolution 400 m for the 100-and 200-year return periods, respectively.

The improvements in volume conservation through identifying adjacent non-flooded cells that are likely to be flooded due to elevation differences vary depending on the spatial resolution. Using the average from the percentage of volume conservation within the four maps, the post-processing step presents improved volume conservation estimates for lower spatial resolutions when compared to that of the higher resolution downscaled maps. The average improvement in downscaled maps at 300m and 400m resolution was approximately 11% and 13% compared to the 0% and 2% increases seen in the downscaled maps with 20-m and 40-m resolutions.

Table 4: Volume conservation accuracies for the downscaled floodplain maps following the identification of neighbouring flooded cells

<b>Resolution of Downscaled Floodplain Map (m)</b>	<b>Calgary</b>		<b>New Brunswick</b>	
	<b>100-Year Volume Conserved (%)</b>	<b>200-Year Volume Conserved (%)</b>	<b>100-Year Volume Conserved (%)</b>	<b>200-Year Volume Conserved (%)</b>

20	101	85	117	117
40	98	93	88	89
60	95	94	81	79
80	94	93	80	77
100	92	93	82	80
200	90	92	87	82
300	88	95	95	92
400	89	96	97	90

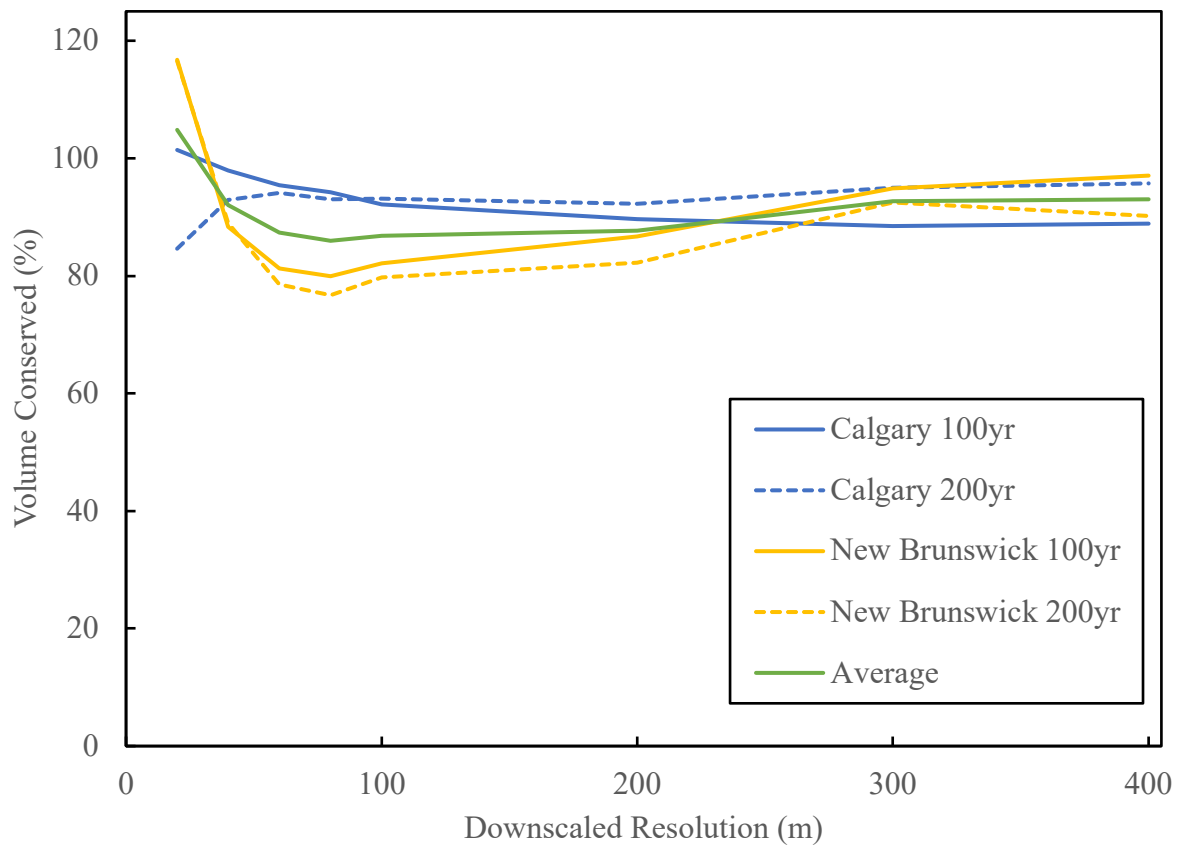


Figure 47: Volume Conservation following the identification of neighbouring flooded cells

#### 6.4 Flood Depth Difference Analysis

With efforts of further identifying the ability of the downscaling methodology, two flood depth difference maps were produced using the difference between the low-resolution floodplain map and 100m spatial resolution floodplain maps for Calgary

and New Brunswick. The flood difference is calculated through subtracting the low-resolution flood map from the 100m resolution map. The two flood difference maps use the 100-year floodplain map to derive the final flood depth difference. Two main takeaways can be observed within the maps, namely the impact on the centre of the flooded water depths and the ability to derive the outer edges of the flood area boundary.

The flood depth difference map for Calgary, presented in Figure 48, shows the flood depth difference along the Bow and Elbow River Basin. The added maximum flood depth difference of + 4.05m occurs where the low-resolution map fails to identify the flooded area. Through the combination of interpolating the downscaled results within the scattered plot and the post-processing tool of looking through non-flooded cells that can be potentially flooded, the downscaling methodology has identified further flooded areas under inundation conditions. Also visible within the flood difference map are a few of the original square pixels from the low-resolution floodplain map, where the downscaled flood cells received a maximum flood depth for the many low-resolution cells. This shows the ability of the map to first conserve the water surface elevation heights, while establishing the flooded cells. Cells where the flood depth difference shows lesser flood depths when compared to the low-resolution map are those where observations using the 100m spatial resolution present no flooding or lower flood depths due to the elevation from the shoreline presence.

The flood depth difference map for New Brunswick, presented in Figure 49, shows the flood depth difference along the St John River Basin. When compared to the flood difference map for Calgary, an additional number of streams within the model present water depths that are similar to their prior flood depth. Conserving flood depths within the downscaling methodology resulted in this similarity of flood depths between the two maps. The downscaling approach has further resulted in the high-resolution elevation data identifying areas in the basin where less flooding exists than the low-resolution map projected, which has led to a maximum increased flood depth difference of + 0.42m and a maximum decreased flood depth difference of - 0.62m. The increased flood depths have resulted from the scattered interpolant and post-processing techniques identifying further elevation cells that can be flooded.

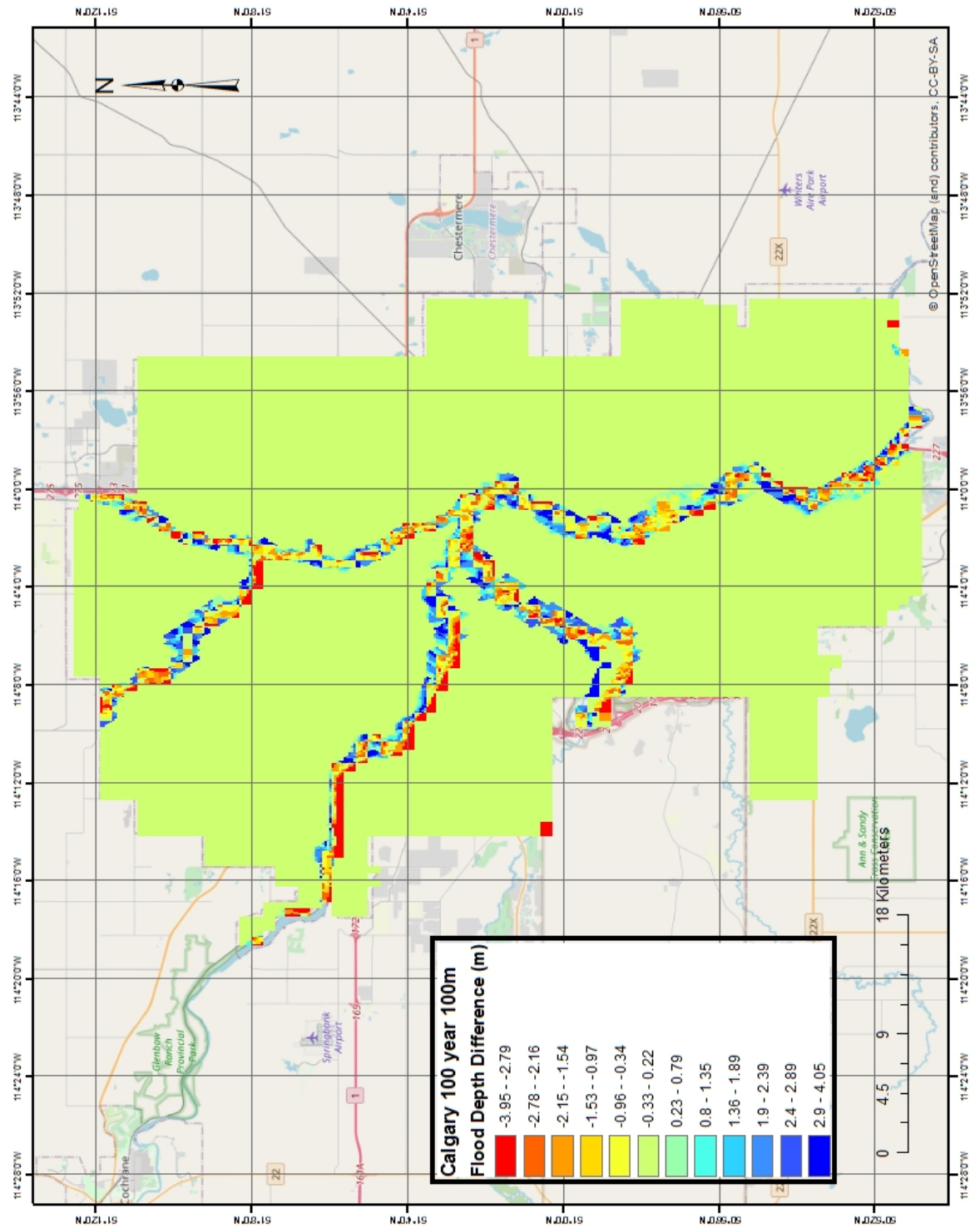


Figure 48: Flood Depth Difference Map between the Low-Resolution floodplain map and 100 m downsampled floodplain map for the 100-year flood event in Calgary



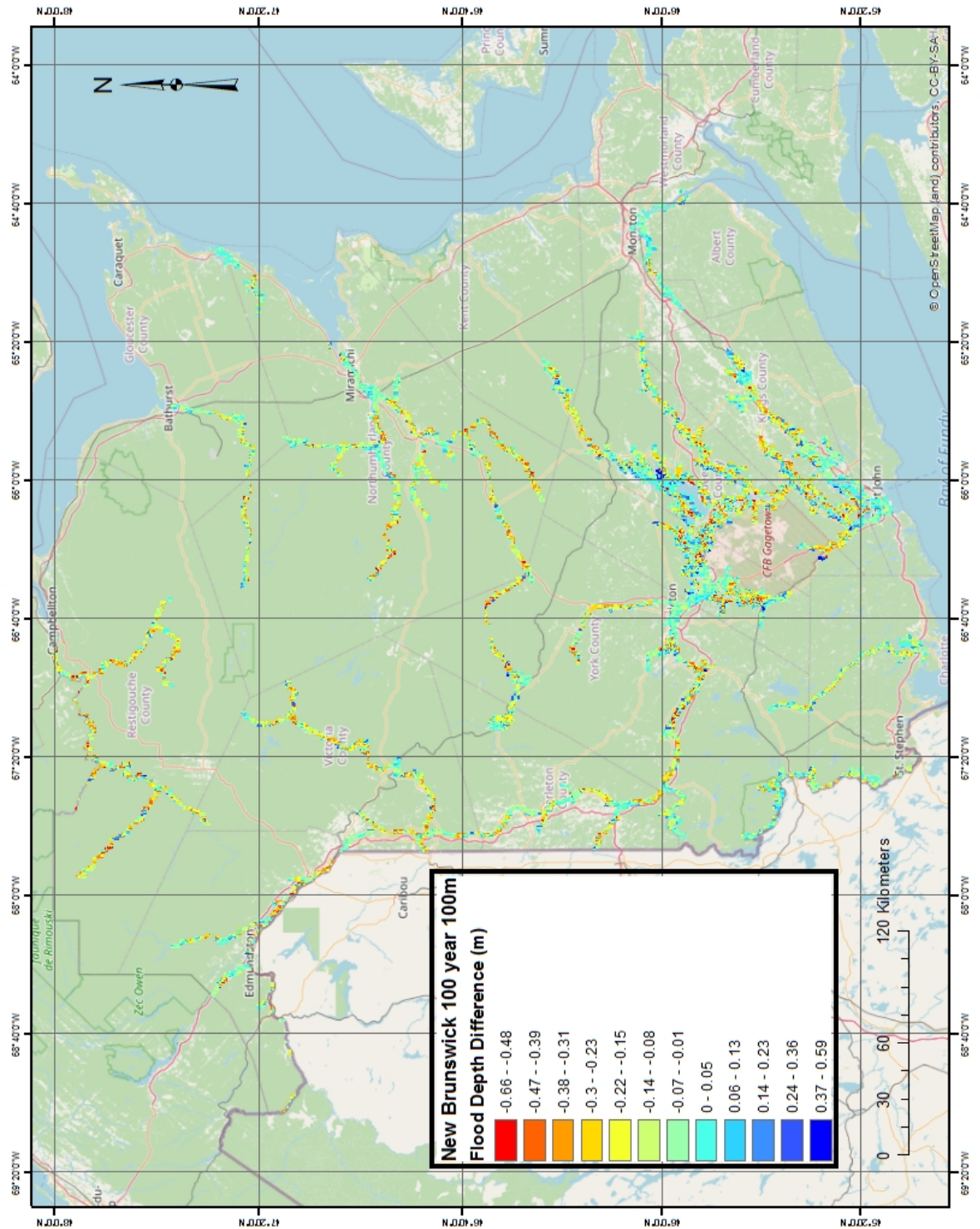


Figure 49: Flood Depth Difference Map between the Low-Resolution floodplain map and 100 m downscaled floodplain map for the 100-year flood event in New Brunswick

## 6.5 Computational Time Requirements

Given the importance of considering computational time in downscaling, a computational time study has been performed that takes into account the time taken for completion within the three main stages of the downscaling. The computational times will be different depending on the size of the floodplain map being downscaled and the size of the reduced DEM produced in the pre-processing steps. The two selected case studies represent an appropriate local scale map, the Bow and Elbow River Basin in Calgary, and a provincial scale map, the St. John River Basin in New Brunswick. With similar computational times for the 100-year and 200-year floodplain maps for the two respective case studies, the computation time study is completed for producing the 100-year maps for both Calgary and New Brunswick case studies. The computational time study was performed on a 3.40 GHz Intel Core with 16GB of memory with 64-bit operating system.

The computational time for downscaling performed in the local scale Calgary case study, which can be seen in Table 5, presents low time steps during each stage of the downscaling process for all performed resolutions. The columns represent the three main steps of the downscaling process and include the downscaling methodology (Subsection 5.3.2), adjacent flooding cell search, and mass-conservation approach (both found in Subsection 5.3.3). Due to the relationship between the processing time and the matrix size of the inputted high-resolution DEM, the time steps increase when downscaling to higher resolutions. To achieve adequate resolutions of 100m x 100m grid size, the total time taken for downscaling is only 1.603s. The ability to produce high-resolution maps at local scales with steps involving lesser time allows large region floodplain maps to be applied for municipalities and cities, while retaining resolution, through a timely process of downscaling. Furthermore, the capability of implementing the downscaling approach within a reasonable time of 49.825s to gain spatial resolutions of 20m x 20m grid size further demonstrates its capacity to produce high resolution results in a timely manner for local scale studies.

Table 5: Computational Time Study for Calgary

<b>Resolution (m)</b>	<b>Downscaling Time Step (s)</b>	<b>Adjacent Cells Time Step (s)</b>	<b>Mass-conservation Time Step (s)</b>
20	11.757	20.160	17.908
40	2.818	4.382	1.88
60	1.267	1.957	0.880
80	0.735	1.131	0.531
100	0.501	0.737	0.365
200	0.204	0.275	0.176
300	0.111	0.171	0.135
400	0.309	0.159	0.140

Due to the difference in scale for the two case studies, the provincial scale New Brunswick case study involved much longer processing times. The full computational time study can be seen in Table 6. When comparing the computational time for achieving spatial resolutions of 100m x 100m grid size, the time increases by 92 times for the New Brunswick case study, involving a computational time of 147.961s (2.46 minutes). While the time consumed increases drastically, the overall ability to improve the spatial resolution to resolutions adequate for identifying shorelines within a low time period is effective for a region of provincial scale. Downscaling to 20m spatial resolutions presents further increase of time required for processing when compared to that of the 100m resolution. A total time of 10,192.669s (169.88 minutes) was required to downscale the New Brunswick floodplain map to 20m spatial resolution. This presents a challenge in performing high-resolution maps at large scale, due to the increased number of cells incorporated within the mapping. The cell difference between the 20m resolution DEM and 100m resolution DEM leads to longer processing time, being 68.9 times longer for the 20m resolution map. With a DEM matrix size of 2876 x 4365 for the 100m resolution map, the downscaling approach can be performed at far greater computational speeds when compared to a DEM matrix size of 14378 x 21825 for the 20m resolution model. This also

necessitates application of a floodplain buffer to reduce computational time through limiting the number of cells involved in the downscaling methodology.

Table 6: Computational Time Study for New Brunswick

<b>Resolution (m)</b>	<b>Downscaling Time Step (s)</b>	<b>Adjacent Cells Time Step (s)</b>	<b>Mass-conservation Time Step (s)</b>
20	1860.290	6514.555	1817.824
40	293.282	823.758	149.389
60	122.657	297.320	68.0126
80	66.774	143.991	37.778
100	41.411	82.387	24.153
200	11.011	16.395	6.445
300	5.520	6.928	3.208
400	3.605	4.020	2.082

Two noteworthy findings of the computational time study are the increased time required for producing mass conservation conditions when the downscaled water volume is greater than the low-resolution water volume and the impact the size and resolution of the inputted DEM have on the final computational time. When volume estimations from the downscale floodplain maps are greater, the required conditions or reducing the flood depth and adjusting cells less than 0m of flood depth to 0m requires more computational time in comparison to adding water depths. While only three maps required reducing water volumes, due to the restriction of water depths to the occupied low-resolution cell, the mass conservation process for this condition can involve longer computational times. The cell size of the inputted DEM also plays a role in the computational time, as the downscaling approach takes longer when processing DEM matrixes of higher cell size. The overall computational time can be further reduced by employing pre-processing steps to reduce the DEM size by applying a floodplain buffer.

## 7. Conclusion

The study consisted of two research objectives related to floodplain mapping strategies in Canada. With the escalating exposure of population, property, and infrastructure to flooding events, floodplain management policies will become more valuable in reducing the vulnerability of cities to flooding across Canada. Floodplain mapping is a vital tool that can be implemented to identify areas susceptible to flooding and limit damage on account of development policies. While large region floodplain mapping is becoming more feasible due to improvements made within Global Flood Models, higher spatial resolution in the maps has had to be sacrificed due to current technology and computational limits. For large region maps to be able to be implemented at local scale to identify flood risks, downscaling techniques are required to improve the final spatial resolution of the floodplain maps.

The first research objective of the study was to *Identify the Current State of Floodplain Mapping Across Canada*. Provincial and territorial governments are responsible for the production of floodplain maps and floodplain management within their provincial jurisdiction. The Flood Damage Reduction Program, established in 1975, introduced funds and strategies for floodplain mapping through split funding from the federal and provincial governments and technical guidance for floodplain maps. Following the closure of the program, the production and maintenance of floodplain maps across Canada has varied and further efforts are required in the production of floodplain maps. There is a range of flood standards applied in floodplain mapping and management across Canada, depending on the level of concern in each province and territory with regard to flooding. NRCAN has established a Federal Flood Mapping Guideline series to improve the production of floodplain mapping across Canada, which includes several documents that discuss technical terminology and methods to produce floodplain maps. The current state of floodplain mapping in Canada presents issues involving a lack of maintenance, production, and funding for floodplain mapping. Large region floodplain maps are a realistic solution to the aforementioned issues, as the maps are produced in reasonable time and can cover all communities in the country.

The second research objective of the study was to *Develop and evaluate an appropriate downscaling methodology for practical application with low-resolution floodplain maps*. Mohanty and Simonovic (2020a) produced a study that involved the implementation of a national floodplain mapping framework for Canada. However, current spatial resolutions of large region maps are inadequate for identifying local scale flood risks, with the resolution of the national floodplain maps being at 1 km. Three downscaling methodologies to improve spatial resolution in large region floodplain maps were analysed for their potential to be implemented to improve the resolution of the national floodplain maps. The two-tiered downscaling approach was proposed due to its accuracy in deriving flood extent and ability to achieve resolutions similar to that of the national floodplain map. The 2D downscaling approach was implemented and enhanced with additional techniques to improve the downscaling process. The downscaling methodology was then performed on the Bow and Elbow River Basin (Calgary – city scale study area) and St John River Basin (New Brunswick – provincial scale study area) case studies. Volume conservation estimates presented the flooded volume to be conserved effectively prior to a mass-conservation method, to ensure that no flooded volume of water was lost during the downscaling process. The downscaled 100 m floodplain maps present an improved ability to identify local flood risks through ideal computational times, and improvements in deriving flood extent boundaries and classifying property exposure to specific flood depths.

A few limitations were identified following the performance of the downscaling methodology, and future work should focus on the following :

*Test the downscaling methodology with additional case studies:* Although the methodology was performed on a city scale region and provincial scale region, further implementation of the methodology for the other basins studied in Mohanty and Simonovic (2021a) would ensure greater accuracy in the downscaling methodology and identify any further limitations of the methodology.

*Improve the mass-conservation method to find additional flooded cells:* The mass conservation post-processing method was performed to ensure that the final flooded volume of water is equal to the low-resolution flooded volume of water. While the added flood depths to reach mass-conservation conditions are low, the shorelines of the flood model have the potential to have depths that would lead to adjacent cells continuously being inundated during the iteration process. Performing a step where these two post-processing steps can be simultaneous could increase the overall accuracy.

*Limit the discontinuities in the downscaled floodplain maps:* The low-resolution flood model for New Brunswick presented discontinuities in the predicted flooding events. Performing other downscaling methodologies would allow deeper knowledge and better understanding of how to effectively limit the discontinuities in the final downscaled model so as to improve accuracy of the model.

*Application of the downscaling methodology for zoning and floodplain regulations:* While the procedure for producing the low-resolution, national region floodplain map for Canada includes detailed hydrologic and hydraulic analysis in determining flood depths, the downscaling methodology focuses on reprojecting the determined volume of flooded water over a higher resolution DEM. The established downscaling methodology does not include any further hydrologic and hydraulic to determine the downscaled flood depths. Although the downscaled maps act as a useful tool for communities that lack any or updated mapping, the ability of the methodology to be implemented for determining land zoning and regulations towards floodplain management strategies is limited due to the absence of further hydrologic and hydraulic processes.

Overall, the development of large region floodplain mapping strategies has presented the possibility of replacing local scale mapping efforts. Large region mapping reduces the amount of time and funding required for the mapping process, as it has the capability of mapping the entire country of Canada. The mapping includes smaller communities that previously lacked floodplain mapping due to inadequate

funding and not being identified as requiring maps. Previous limitations involved in inadequate spatial resolution for identifying local flood risks can be solved with downscaling applications. The downscaling methodology implemented for basins within the national floodplain map presents a realistic solution for improving the spatial resolution of the maps to 100 m. The 100 m maps for both the local (Calgary) and provincial (New Brunswick) scale studies present an enhanced flooded boundary, individualised flood depths, and accurate volume conservation, while being produced within reasonable computational times. With further adaptations of hydrologic and hydraulic components within the downscaling procedure, large region mapping with the combination of downscaling procedures have a great potential to be practically effective for local-scale floodplain mapping.



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## 9. Appendices

### Appendix A: Summary of Ontario Conservation Authority Floodplain Practices

Conservation Authority (CA)	Flood Standard	URL
Mattagami Region CA	Maximum of 100 year flood event or Timmins Flood event standard	<a href="https://www.ontario.ca/laws/regulation/060165">https://www.ontario.ca/laws/regulation/060165</a>
North Bay – Mattawa CA	100 year flood event for Chippewa Creek and its tributaries below the North Bay Escarpment, Parks Creek, the Mattawa River in the town of Mattawa and the La Vase River Timmins Flood event standard used for rest of CA	<a href="https://www.ontario.ca/laws/regulation/060177/v1">https://www.ontario.ca/laws/regulation/060177/v1</a>
Nickel District CA	Maximum of 100 year flood event or Timmins Flood event standard Wanapitei Lake uses maximum flood allowance elevation of 267.95m	<a href="https://www.ontario.ca/laws/regulation/060156">https://www.ontario.ca/laws/regulation/060156</a>
Essex Region CA	March 1985 Flood event used for main and east branch of the Ruscom River, and its tributaries within the Town of Lakeshore and Kingsville March 1985 Flood event used for main and north branch of Canard River in the Town of LaSalle, Concessions I and II, and on main branch of the Canard River in the Town of Amherstburg, Concessions I, II, III, and IV 100 Year Flood Standard used for rest of CA	<a href="https://www.ontario.ca/laws/regulation/060158">https://www.ontario.ca/laws/regulation/060158</a>
Lower Thames Valley CA	1937 Flood event standard on the River Thames – equivalent to 250 year flood or 100 Year Flood level plus wave uprush	<a href="https://www.ontario.ca/laws/regulation/060152">https://www.ontario.ca/laws/regulation/060152</a>
St. Clair Region CA	100 year flood event for Perch Creek 100 year flood plus wave uprush for Lake Huron, Lake St. Clair and St. Clair River in the Great Lakes-St. Lawrence River System Hurricane Hazel Flood event standard used for rest of CA (approx. 250 year return period)	<a href="https://www.ontario.ca/laws/regulation/060171">https://www.ontario.ca/laws/regulation/060171</a>
Ausable Bayfield CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush	<a href="https://www.ontario.ca/laws/regulation/060147">https://www.ontario.ca/laws/regulation/060147</a>
Upper Thames River CA	1937 flood event standard on the River Thames – equivalent to 250 year flood	<a href="https://www.ontario.ca/laws/regulation/060157">https://www.ontario.ca/laws/regulation/060157</a>

Kettle Creek CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Erie	<a href="https://www.ontario.ca/laws/regulation/060181">https://www.ontario.ca/laws/regulation/060181</a>
Catfish Creek CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Erie	<a href="https://www.ontario.ca/laws/regulation/060146">https://www.ontario.ca/laws/regulation/060146</a>
Long Point Region CA	Maximum of 100 year flood event, or 100 year flood level plus wave uprush for Lake Erie	<a href="https://www.ontario.ca/laws/regulation/060178">https://www.ontario.ca/laws/regulation/060178</a>
Maitland Valley CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Huron	<a href="https://www.ontario.ca/laws/regulation/r06164">https://www.ontario.ca/laws/regulation/r06164</a>
Grand River CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Erie	<a href="https://www.ontario.ca/laws/regulation/060150">https://www.ontario.ca/laws/regulation/060150</a>
Niagara Peninsula CA	Hurricane Hazel Flood event standard (approx. 250 year return period) applies to the watersheds associated with Shriner's Creek, Ten Mile Creek, and Beaverdams Creek 100 year flood event standard plus wave uprush applies to Lake Ontario and Lake Erie 100 year flood event standard applies to rest of CA	<a href="https://www.ontario.ca/laws/regulation/060155">https://www.ontario.ca/laws/regulation/060155</a>
Hamilton Region CA	100 year flood event standard plus wave uprush applies to Lake Ontario 100 year flood level applies to Hamilton Harbour 100 year flood level applies to Watercourses WCO, WCI, WC2, 3, 4, 5.0, 5.1, 6.0, 6.1, 6.2, 6.3, 6.4, 7.0, 7.1, 7.2, 7.3, 8.0, 9.0, 10.0, 10.1, 10.2, 11.0 and 12.0 as indicated on Map Figure 1 of Project 98040-A Hurricane Hazel Flood event standard applies to rest of CA (approx. 250 year return period)	<a href="https://www.ontario.ca/laws/regulation/060161">https://www.ontario.ca/laws/regulation/060161</a>
Halton Region CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Ontario and Hamilton Harbour	<a href="https://www.ontario.ca/laws/regulation/060162">https://www.ontario.ca/laws/regulation/060162</a>
Credit Valley CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100	<a href="https://www.ontario.ca/laws/regulation/060160">https://www.ontario.ca/laws/regulation/060160</a>

	year flood event, and 100 year flood level plus wave uprush for Lake Ontario	
Saugeen Valley CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Huron	<a href="https://www.ontario.ca/laws/regulation/060169">https://www.ontario.ca/laws/regulation/060169</a>
Grey Sauble CA	100 year flood event standard plus wave uprush applies to Lake Huron and Georgian Bay 100 year flood event applies to Sauble River Watershed Timmins Flood event standard applies to rest of CA	<a href="https://www.ontario.ca/laws/regulation/060151">https://www.ontario.ca/laws/regulation/060151</a>
Nottawasaga Valley CA	Maximum of Timmins Flood event standard, 100 year flood event, and 100 year flood level plus wave uprush for Lake Ontario and Lake Erie	<a href="https://www.ontario.ca/laws/regulation/060172/v1">https://www.ontario.ca/laws/regulation/060172/v1</a>
Toronto and Region CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Ontario	<a href="https://www.ontario.ca/laws/regulation/r06166">https://www.ontario.ca/laws/regulation/r06166</a>
Lake Simcoe Region CA	100 year flood event standard applies to Bunker's Creek and Sophia Creek Timmins Flood event standard applies to Talbot River and the Trent-Severn waterway 100 year flood level plus wave uprush applied to Lake Simcoe Hurricane Hazel Flood event standard applies to rest of CA (approx. 250 year return period)	<a href="https://www.ontario.ca/laws/regulation/060179">https://www.ontario.ca/laws/regulation/060179</a>
Kawartha Region CA	Maximum of Timmins Flood event standard and 100 year flood event	<a href="https://www.ontario.ca/laws/regulation/060182">https://www.ontario.ca/laws/regulation/060182</a>
Central Lake Ontario CA	100 year flood event standard applies to Pringle Creek and Darlington Creek 100 year flood level plus wave uprush applies to Lake Ontario Hurricane Hazel Flood event standard applies to rest of CA (approx. 250 year return period)	<a href="https://www.ontario.ca/laws/regulation/060042">https://www.ontario.ca/laws/regulation/060042</a>
Otonabee Conservation	Water surface elevations govern for the following lakes: Rice Lake – 187.90m Stony Lake – 235.95m Clear Lake – 235.96m Lovesick Lake – 242.16m Deer Bay – 244.31m Buckhorn Lake – 247.12m	<a href="https://www.ontario.ca/laws/regulation/060167">https://www.ontario.ca/laws/regulation/060167</a>



	Chemong Lake – 247.12m	
	Pigeon Lake – 247.12m	
	Katchivanooka Lake – 233.68m	
	Lower Buckhorn Lake – 244.31m	
	Timmins Flood event standard applies to rest of CA	
Ganaraska Region CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and 100 year flood level plus wave uprush for Lake Ontario	<a href="https://www.ontario.ca/laws/regulation/R06168">https://www.ontario.ca/laws/regulation/R06168</a>
Crowe Valley CA	Maximum of Hurricane Hazel Flood event standard (approx. 250 year return period), 100 year flood event, and Timmins Flood event standard	<a href="https://www.ontario.ca/laws/regulation/060159">https://www.ontario.ca/laws/regulation/060159</a>
Lower Trent Region CA	Water surface elevations govern for the following lakes and dams: Rice Lake – 187.9m Below Dam #1 (Trenton) – 77.2m Below Dam #2 (Sidney) – 81.3m Below Dam #3 (Glen Miller) – 87.7m Below Dam #4 (Batawa) – 95.7m Below Dam #5 (Trent) – 101.7m Below Dam #6 (Frankford) – 107.9m Below Dam #7 (Glen Ross) – 113.5m Below Dam #8 (Meyers) – 117.9m Below Dam #9 (Hagues Reach) – 128.1m Below Dam #10 (Ranney Falls) – 143.4m Below Dam #11 (Campbellford) – 148.3m Below Dam #12 (Crowe Bay) – 154.3m Below Dam #13 (Healy Falls) – 175.5m Below Dam #14 (Hastings) – 186.7m 100 year flood level plus wave uprush applies to Lake Ontario Timmins Flood event standard applies to rest of CA	<a href="https://www.ontario.ca/laws/regulation/060163">https://www.ontario.ca/laws/regulation/060163</a>
Quinte CA	100 year flood event standard and 100 year flood level plus wave uprush for Lake Ontario	<a href="https://www.ontario.ca/laws/regulation/090319/v1">https://www.ontario.ca/laws/regulation/090319/v1</a>
Cataraqui Region CA	100 year flood event standard and 100 year flood level plus wave uprush for Lake Ontario and the St. Lawrence River	<a href="https://www.ontario.ca/laws/regulation/060148">https://www.ontario.ca/laws/regulation/060148</a>
Mississippi Valley CA	100 year flood event standard	<a href="https://www.ontario.ca/laws/regulation/060153">https://www.ontario.ca/laws/regulation/060153</a>
Rideau Valley CA	100 year flood event standard	<a href="https://www.ontario.ca/laws/regulation/r06174">https://www.ontario.ca/laws/regulation/r06174</a>

South Nation River CA	100 year flood event standard and 100 year flood level plus wave uprush for the St. Lawrence River	<a href="https://www.ontario.ca/laws/regulation/r06170">https://www.ontario.ca/laws/regulation/r06170</a>
Raisin Region CA	100 year flood event standard and 100 year flood level plus wave uprush allowance	<a href="https://www.ontario.ca/laws/regulation/060175">https://www.ontario.ca/laws/regulation/060175</a>
Sault Ste Marie Region CA	Maximum of Timmins Flood event standard, 100 year flood event standard and 100 year flood level plus wave uprush for Lake Superior and the Upper and Lower St. Mary's River	<a href="https://www.ontario.ca/laws/regulation/060176">https://www.ontario.ca/laws/regulation/060176</a>
Lakehead Region CA	100 year flood event standard applies to the main channel of the Kaministiquia River 100 year flood level plus wave uprush applies to Lake Superior Timmins Flood event standard applies to rest of CA	<a href="https://www.ontario.ca/laws/regulation/r06180">https://www.ontario.ca/laws/regulation/r06180</a>

## Appendix B: Matlab Scripts for Downscaling

### %%% Downscaling Scheme

```
%Input1 = HR points from buffer
[fp, ncolsf, nrowf, xllcornerf, yllcornerf, cellsizef, nodataf] =
ascii_reader(['C:\Users\jbraden3\Desktop\FinalInputs\NewBrunswick\dem400.asc']);
yulf = yllcornerf+(nrowf*cellsizef)+cellsizef;
xulf = xllcornerf;
[wyf,wxf] = find(fp > 0);
fwf = find(fp > 0);
fp_pts(:,1) = xulf+((wxf*cellsizef)-(cellsizef)/2); %mid cell X
fp_pts(:,2) = yulf-((wyf*cellsizef)+(cellsizef)/2); %mid cell Y
fp_pts(:,3) = fp(fwf); %value of DEM
```

```
%Input2 = CR WSL
```

```
[sgwsl, ncolss, nrowss, xllcorners, yllcorners, cellsizes, nodatas] =
ascii_reader(['C:\Users\jbraden3\Desktop\FinalInputs\NewBrunswick\100wsl.asc']);
yuls = yllcorners+(nrowss*cellsizes)+cellsizes;
xuls = xllcorners;
[wys,wxs] = find(sgwsl > 0);
fws = find(sgwsl > 0);
sgwsl_pts(:,1) = xuls+((wxs*cellsizes)-(cellsizes)/2); %mid cell X
sgwsl_pts(:,2) = yuls-((wys*cellsizes)+(cellsizes)/2); %mid cell Y
sgwsl_pts(:,3) = sgwsl(fws); %value of DEM
```

```
%Input3 = CR Flood Model - Used for volume check
```

```
[depth, ncolsd, nrowd, xllcornerd, yllcornerd, cellsize, nodatad] =
ascii_reader(['C:\Users\jbraden3\Desktop\FinalInputs\NewBrunswick\100flood.asc']);
yuld = yllcornerd+(nrowd*cellsize)+cellsize;
xuld = xllcornerd;
[wyd,wxd] = find(depth > 0);
fwd = find(depth > 0);
depth_pts(:,1) = xuld+((wxd*cellsize)-(cellsize)/2); %mid cell X
depth_pts(:,2) = yuld-((wyd*cellsize)+(cellsize)/2); %mid cell Y
depth_pts(:,3) = depth(fwd); %value of DEM
```

```
[id,Dis]=
```

```
rangesearch(fp_pts(:,1:2),sgwsl_pts(:,1:2),cellsize*1.5,'Distance','Cityblock');
disp(['Found all floodplain points for sgwsl']);
```

```
fpbuff = fp_pts;
fpbuffcoarse = fp_pts;
```

```
for k = 1:length(id)
getxyzid = fpbuff(id{k,1},1:3);
getxyzid(:,4) = id{k,1};
z_sgwsl = sgwsl(wys(k),wxs(k));
for kk = 1:size(getxyzid,1);
if getxyzid(kk,3)<z_sgwsl
fpbuff(getxyzid(kk,4),4) = z_sgwsl-getxyzid(kk,3);
```

```

        else
        end
    end
end

disp(['Downscaled floodplain']);

[idx,Disx]=
rangesearch(fp_pts(:,1:2),depth_pts(:,1:2),cellsizes*1.5,'Distance','Cityblock');
disp(['Found all floodplain points for coarse flood depth']);

for j = 1:length(idx)
getxyzid2 = fpbuffcoarse(idx{j,1},1:3);
getxyzid2(:,4) = idx{j,1};
flooddepth = depth(wyd(j),wxd(j));
for jj = 1:size(getxyzid2,1)
    fpbuffcoarse(getxyzid2(jj,4),4) = flooddepth;
end
end

fpbuffcoarse(:,5) = fpbuff(:,4);

%Findrange all non zero values less than maximum coarse grid corresponding
fz = find(fpbuffcoarse(:,5)>0 & fpbuffcoarse(:,5)<=fpbuffcoarse(:,4));
x = fpbuff(fz,1);
y = fpbuff(fz,2);
z = fpbuff(fz,4);

F = scatteredInterpolant(x,y,z,'nearest','nearest');

%All other x,y values greater than the max. Use findrange greater than
%maximum water level
ffz = find(fpbuffcoarse(:,5)>fpbuffcoarse(:,4));
xq = fpbuff(ffz,1);
yq = fpbuff(ffz,2);

zq = F(xq,yq);

%Findindex
fpbuff(ffz,5) = zq ;
fpbuff(fz, 6) =z;
fpbuff(:, 7)=fpbuff(:,5) +fpbuff(:,6) ;

fpbuffrast(1:nrowsf,1:ncolsf)=0;
for as = 1:length(fpbuff(:,7))
    fpbuffrast(wyf(as,1),wxf(as,1))=fpbuff(as,7);
end

disp(['Finished reading off 3km modeled values at clock set: ', num2str(clock),'...']);

```

toc

```
%Volume check before
totalheight1 = sum(depth_pts(:,3));
volumebefore = totalheight1 * cellsizez * cellsizez;
disp(['Flooded volume before downscaling is ', num2str(volumebefore)]);
```

```
%Volume check after
totalheight2 = sum(fpbuff(:,7));
volumeafter = totalheight2 * cellsizef * cellsizef;
disp(['Flooded volume after downscaling is ', num2str(volumeafter)]);
```

```
%Volume Accuracy
volumedifference = volumeafter - volumebefore;
if volumedifference < 0
    volumedifference = 0 - volumedifference;
end
```

```
volumeaccuracy = 100-((volumedifference/volumeafter)*100);
```

```
disp(['Volume accuracy is ', num2str(volumeaccuracy)]);
```

```
imagesc(fpbuffrast);
```

```
ascii_write(['C:\Users\jbraden3\Desktop\DownscaledModels\Calgary\200yr300m.asc']
, fpbuffrast, xllcornerf, yllcornerf, cellsizef, nodataf);
```

### **%%%Adjacent Scheme**

tic

```
%Input Downscaled Model
```

```
[hr, ncolsh, nrowsh, xllcornerh, yllcornerh, cellsizeh, nodatah] =
ascii_reader(['C:\Users\jbraden3\Desktop\downscaledmodels\example.asc']);
yulh = yllcornerh+(nrowsh*cellsizeh)+cellsizeh;
xulh = xllcornerh;
[wyh,wxh] = find(hr > 0);
fwh = find(hr > 0);
hr_pts(:,1) = xulh+((wxh*cellsizeh)-(cellsizeh)/2); %mid cell X
hr_pts(:,2) = yulh-((wyh*cellsizeh)+(cellsizeh)/2); %mid cell Y
hr_pts(:,3) = hr(fwh);
```

```
%Input Coarse Scale Model
```

```
[depth, ncolsd, nrowsd, xllcornerd, yllcornerd, cellsize, nodatad] =
ascii_reader(['C:\Users\jbraden3\Desktop\FinalInputs\flooddepth.asc']);
```

```

yuld = yllcornerd+(nrowsd*cellsize)+cellsize;
xuld = xllcornerd;
[wyd,wxd] = find(depth > 0);
fwd = find(depth > 0);
depth_pts(:,1) = xuld+((wxd*cellsize)-(cellsize)/2); %mid cell X
depth_pts(:,2) = yuld-((wyd*cellsize)+(cellsize)/2); %mid cell Y
depth_pts(:,3) = depth(fwd); %value of DEM

%Input HR DEM Points
[fp, ncolsf, nrowssf, xllcornerf, yllcornerf, cellsizef, nodataf] =
ascii_reader(['C:\Users\jbraden3\Desktop\FinalInputs\dem.asc']);
yulf = yllcornerf+(nrowssf*cellsizef)+cellsizef;
xulf = xllcornerf;
[wyf,wxf] = find(fp > 0);
fwf = find(fp > 0);
fp_pts(:,1) = xulf+((wxf*cellsizef)-(cellsizef)/2); %mid cell X
fp_pts(:,2) = yulf-((wyf*cellsizef)+(cellsizef)/2); %mid cell Y
fp_pts(:,3) = fp(fwf); %value of DEM

for i=1:length(hr(:,1))
    for j=1:length(hr(1,:))
        if hr(i, j) < 0
            hr(i, j) = 0;
        end
        if fp(i, j) < 0
            fp(i, j) = 0;
        end
    end
end
wsl = fp + hr;

x = wsl;
for i=1:length(fp(:,1))
    for j=1:length(fp(1,:))
        if fp(i, j) > 0 && not(hr(i, j) == 0)
            if i > 1 && i < length(fp(:,1)) && j > 1 && j < length(fp(1,:))
                if fp(i - 1, j) > 0 && hr(i - 1, j) == 0 && wsl(i, j) > wsl(i - 1, j)
                    if hr(i, j) + wsl(i - 1, j) < wsl(i, j)
                        x(i - 1, j) = hr(i, j) + wsl(i - 1, j);
                    end
                end
            end
            if fp(i, j + 1) > 0 && hr(i, j + 1) == 0 && wsl(i, j) > wsl(i, j + 1)
                if hr(i, j) + wsl(i, j + 1) < wsl(i, j)
                    x(i, j + 1) = hr(i, j) + wsl(i, j + 1);
                end
            end
            if fp(i, j - 1) > 0 && hr(i, j - 1) == 0 && wsl(i, j) > wsl(i, j - 1)

```



```

tic
%Input Coarse Scale Model
[depth, ncolsd, nrowd, xllcornerd, yllcornerd, cellsize, nodatad] =
ascii_reader(['C:\Users\jbraden3\Desktop\FinalInputs\flooddepth.asc']);
yuld = yllcornerd+(nrowd*cellsize)+cellsize;
xuld = xllcornerd;
[wyd, wxd] = find(depth > 0);
fwd = find(depth > 0);
depth_pts(:,1) = xuld+((wxd*cellsize)-(cellsize)/2); %mid cell X
depth_pts(:,2) = yuld-((wyd*cellsize)+(cellsize)/2); %mid cell Y
depth_pts(:,3) = depth(fwd); %value of DEM

%Input Downscaled Model
[hr, ncolsh, nrowsh, xllcornerh, yllcornerh, cellsizeh, nodatah] =
ascii_reader(['C:\Users\jbraden3\Desktop\DownscaledModels\example.asc']);
yulh = yllcornerh+(nrowsh*cellsizeh)+cellsizeh;
xulh = xllcornerh;
[wyh, wxh] = find(hr > 0);
fwh = find(hr > 0);
hr_pts(:,1) = xulh+((wxh*cellsizeh)-(cellsizeh)/2); %mid cell X
hr_pts(:,2) = yulh-((wyh*cellsizeh)+(cellsizeh)/2); %mid cell Y
hr_pts(:,3) = hr(fwh);
hr_pts(:,4) = hr_pts(:,3);

%Volume check before
totalheight1 = sum(depth_pts(:,3));
volumebefore = totalheight1 * cellsize * cellsize;
disp(['Flooded volume before downscaling is ', num2str(volumebefore)]);

%Volume check after
totalheight2 = sum(hr_pts(:,3));
volumeafter = totalheight2 * cellsizeh * cellsizeh;
disp(['Flooded volume after downscaling is ', num2str(volumeafter)]);

while volumeafter < volumebefore
    hr_pts(:,4) = hr_pts(:,4) + 0.00001;
    totalheight2 = sum(hr_pts(:,4));
    volumeafter = totalheight2 * cellsizeh * cellsizeh;
end

fpbuffrast(1:nrowsh, 1:ncolsh) = 0;
for as = 1:length(hr_pts(:,4))
    fpbuffrast(wyh(as,1), wxh(as,1)) = hr_pts(as,4);
end

totalheight3 = sum(hr_pts(:,4));
volumeafter2 = totalheight3 * cellsizeh * cellsizeh;
disp(['Flooded volume after downscaling is ', num2str(volumeafter2)]);
imagesc(fpbuffrast);

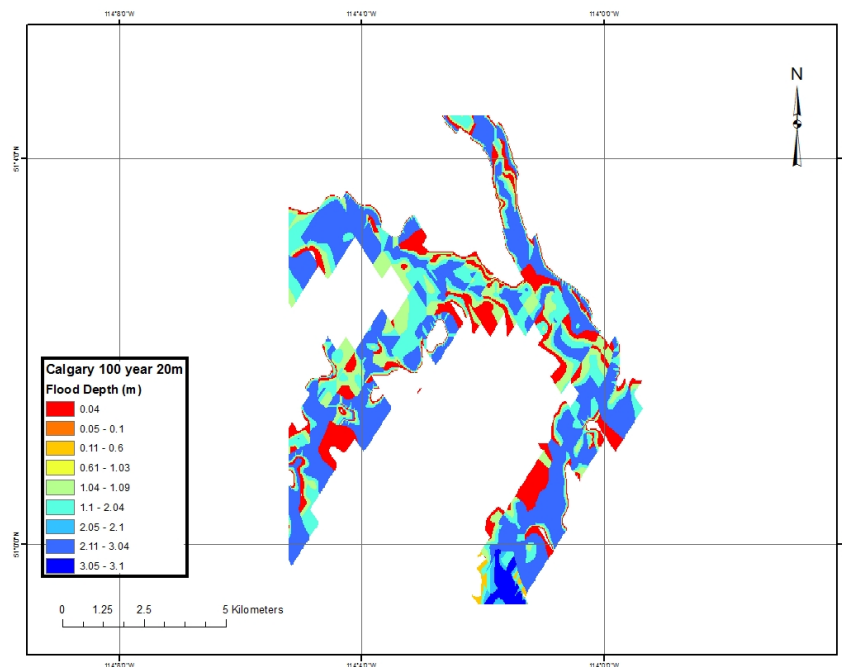
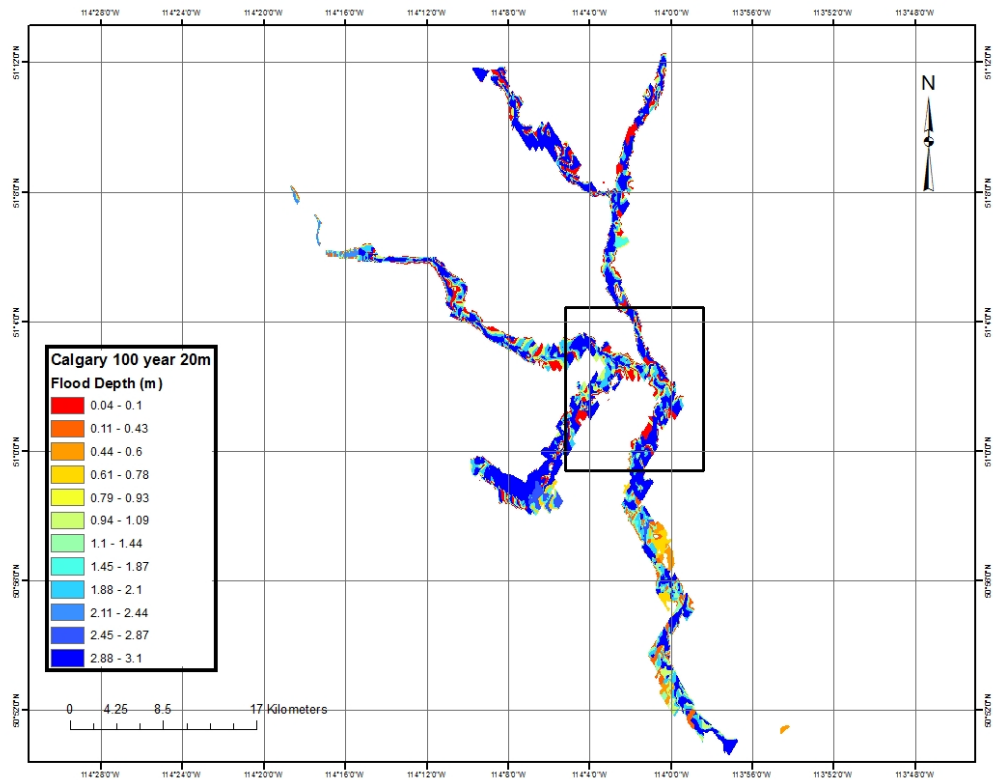
```



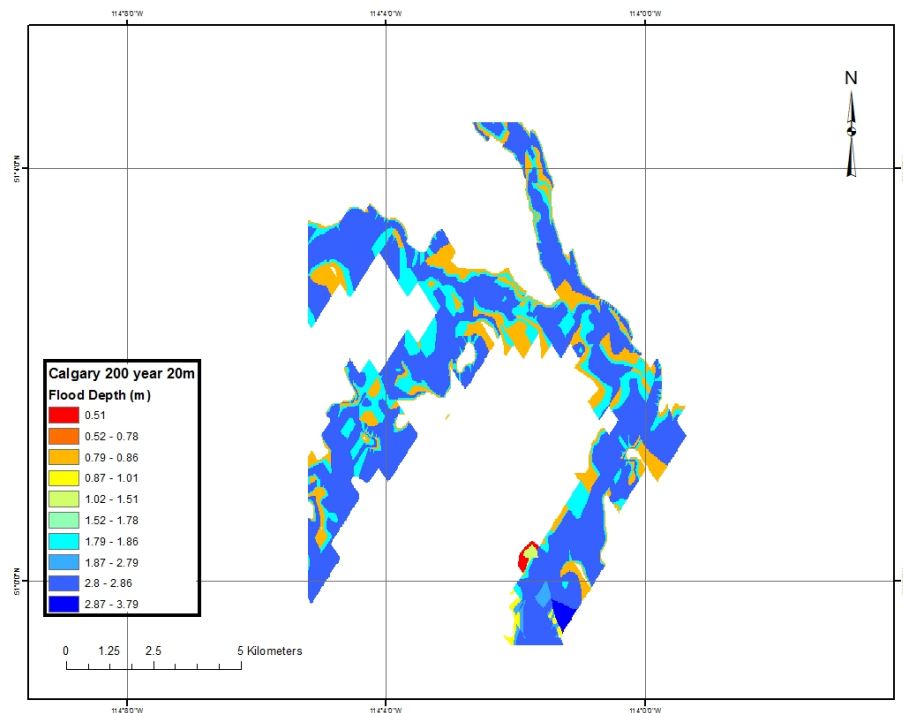
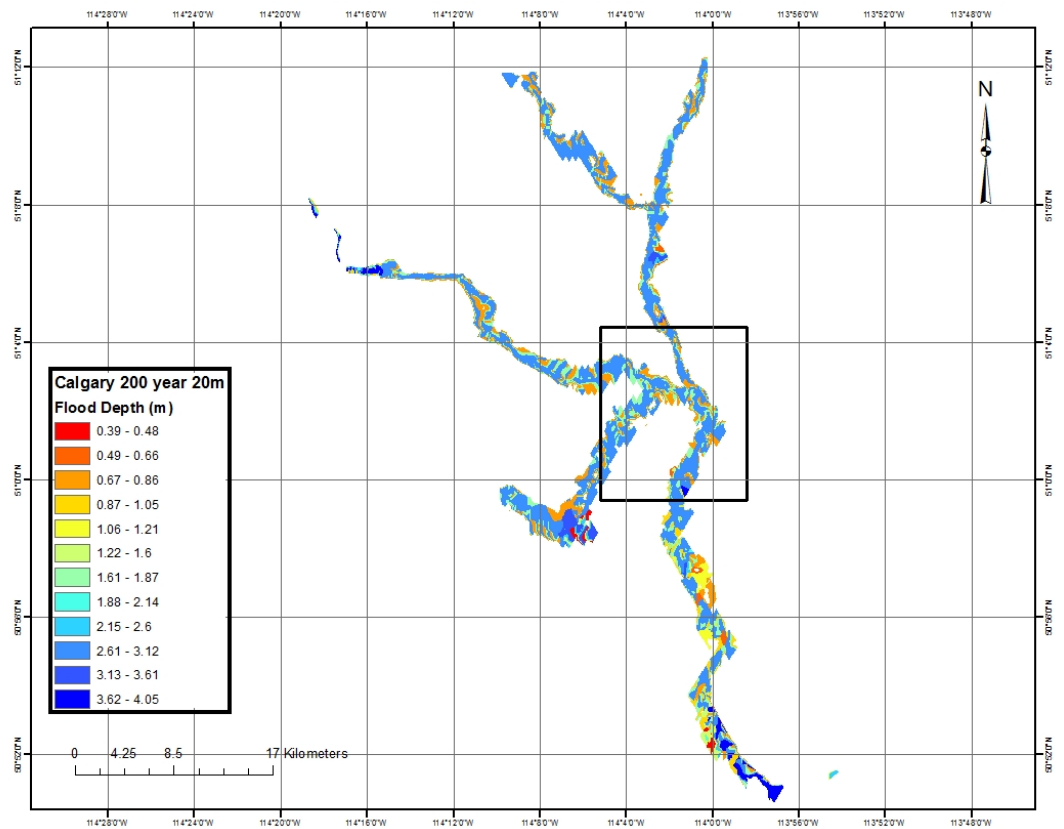
```
toc
ascii_write(['C:\Users\jbraden3\Desktop\DownscaledModels\NewBrunswickMass\20
0yr20m.asc'], fpbuffrast, xllcornerh, yllcornerh, cellsizeh, nodatah);
```

## Appendix C: Calgary Floodplain Maps

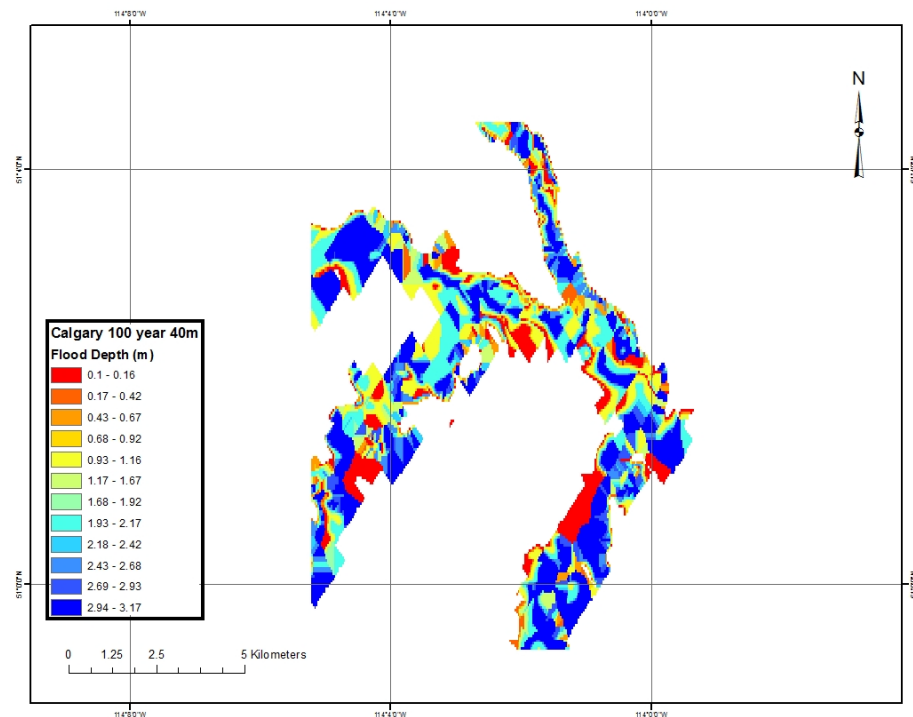
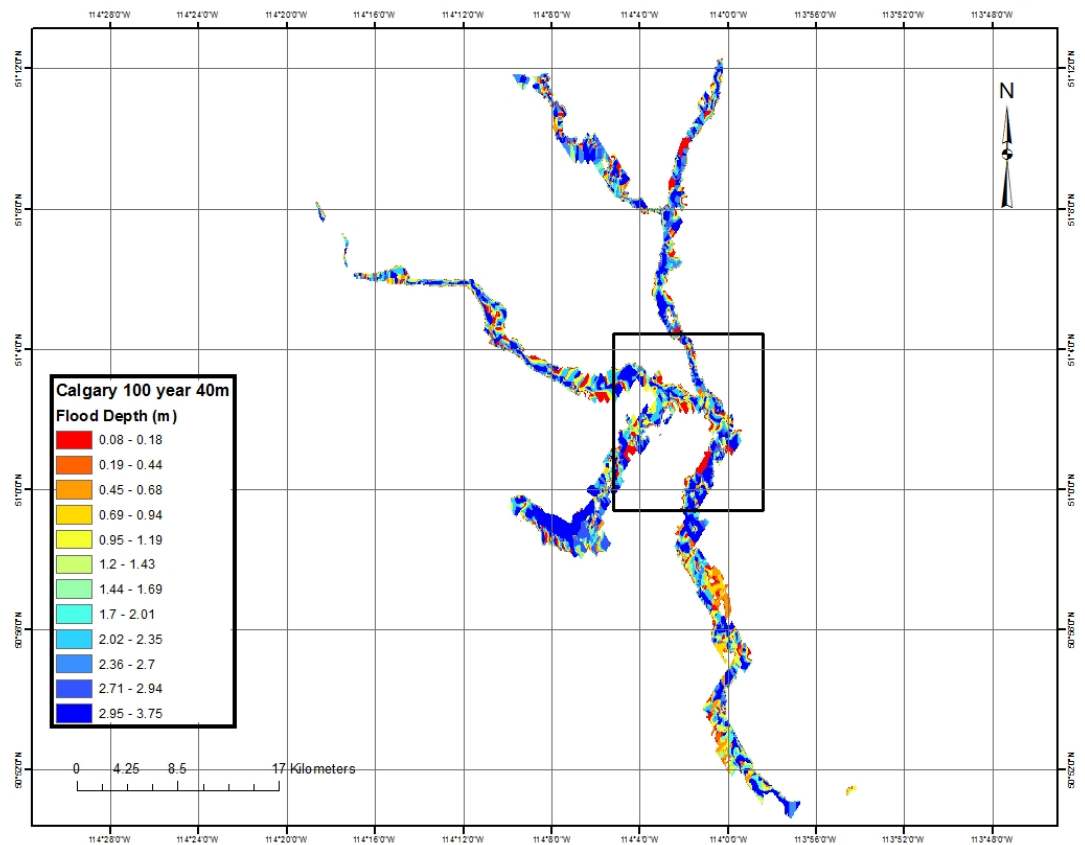
### Appendix C.1: 20m 100 year Floodplain Map



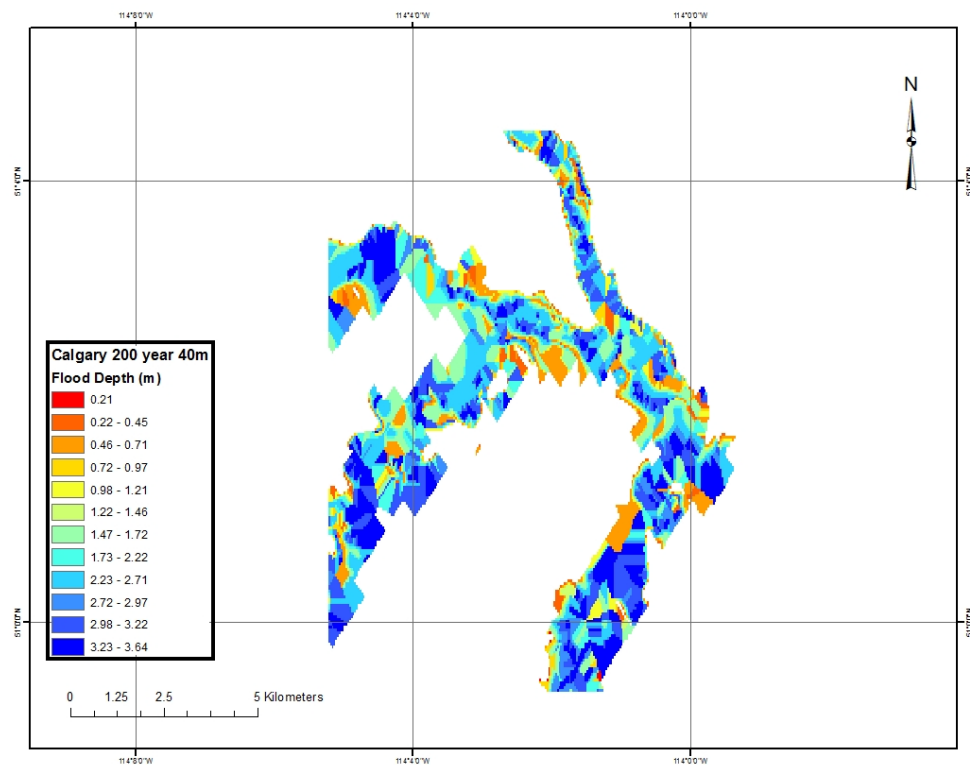
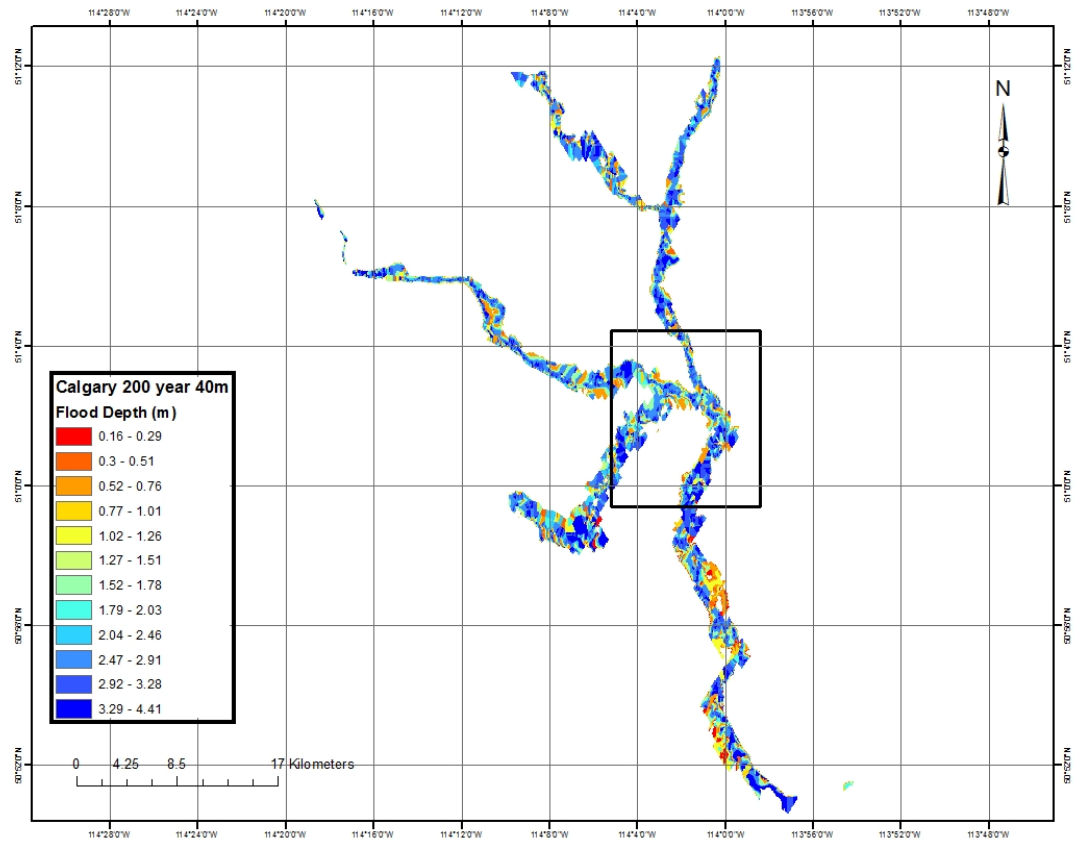
## Appendix C.2: 20m 200 year Floodplain Map



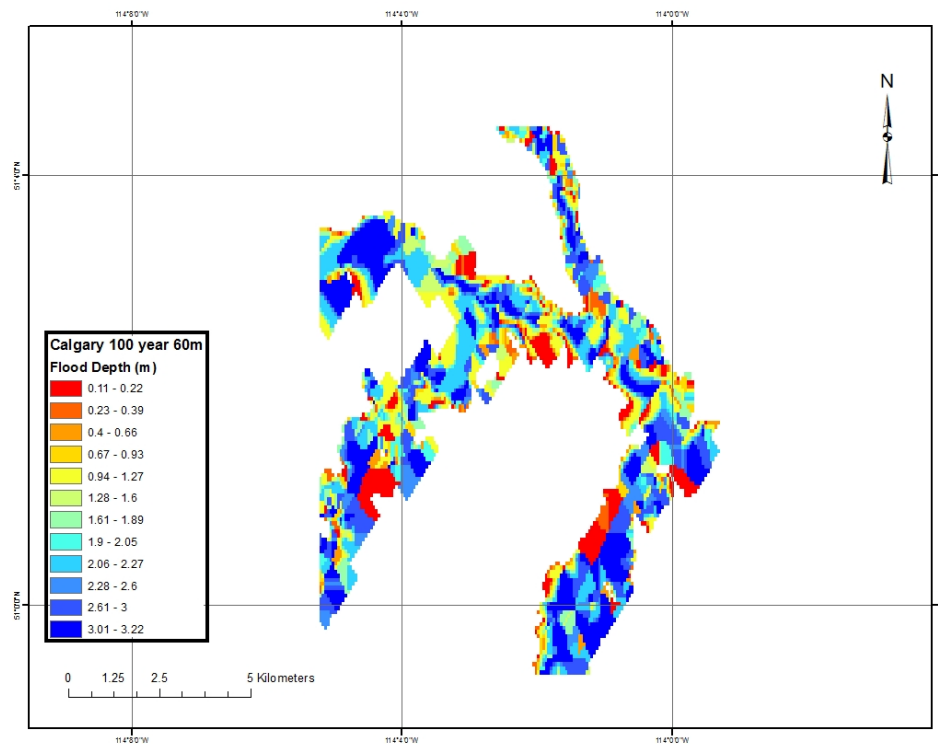
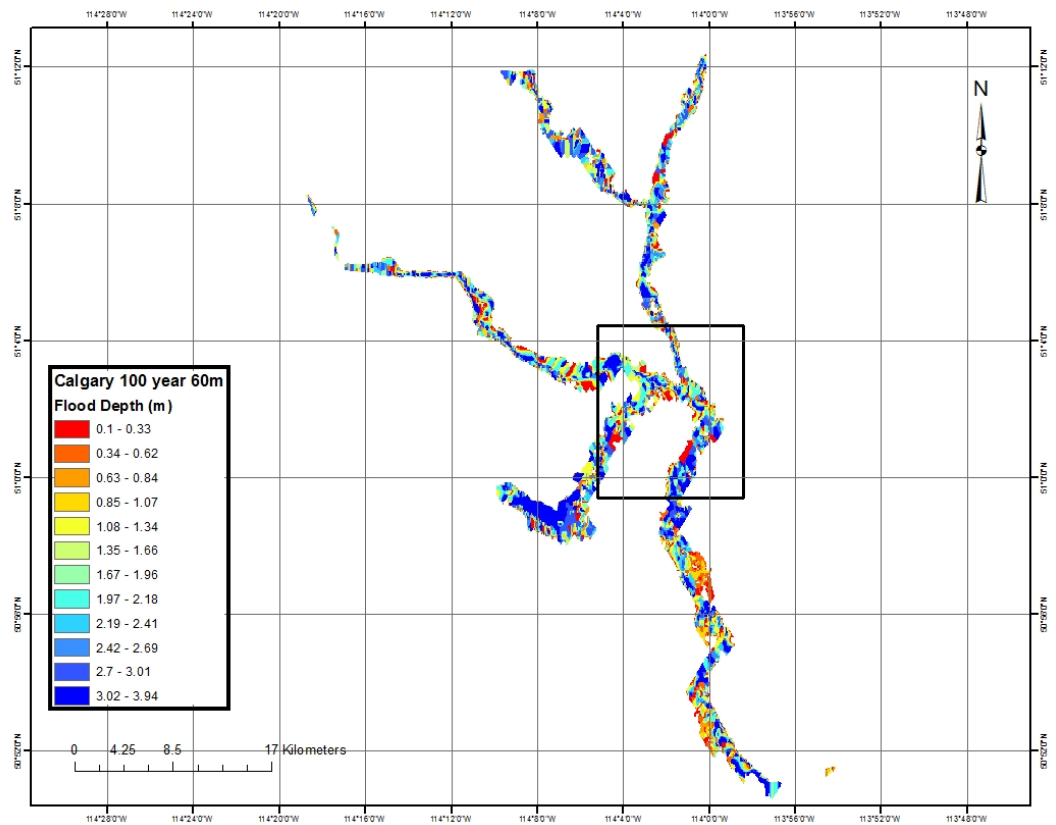
## Appendix C.3: 40m 100 year Floodplain Map



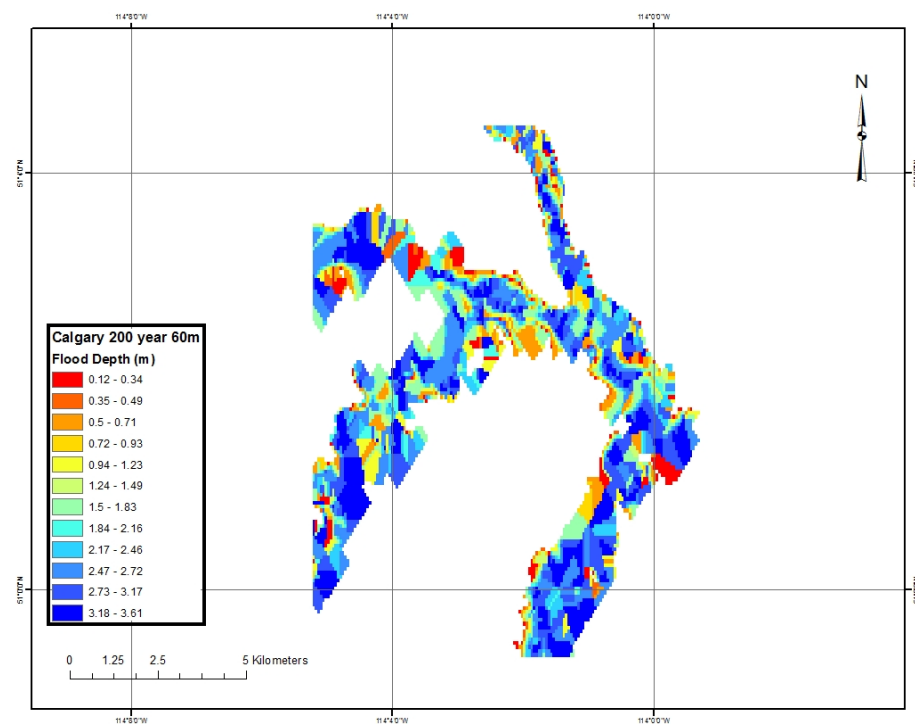
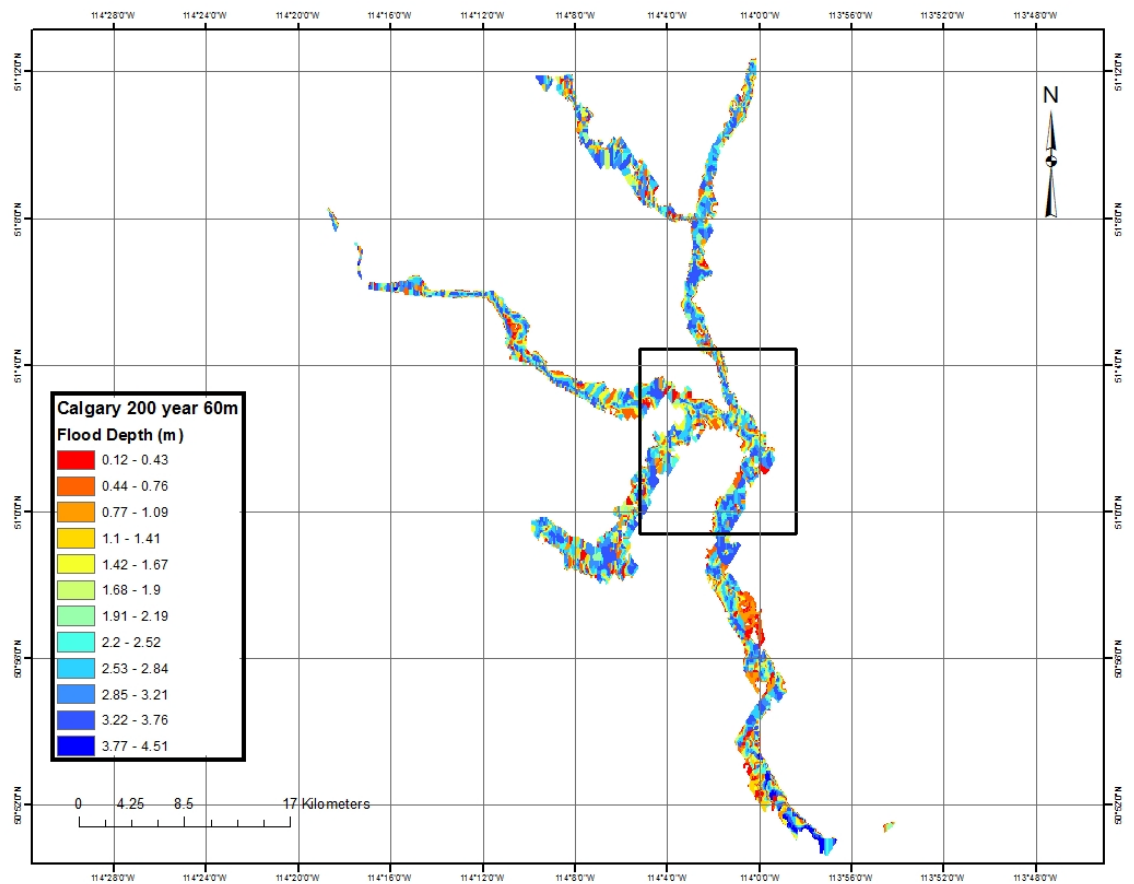
## Appendix C.4: 40m 200 year Floodplain Map



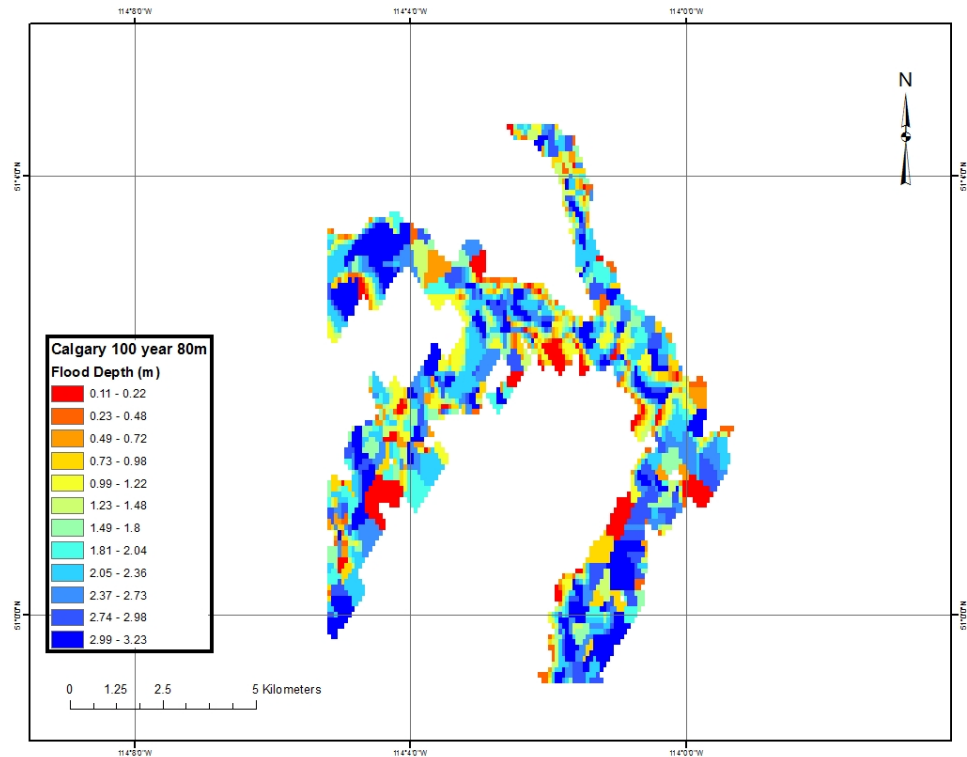
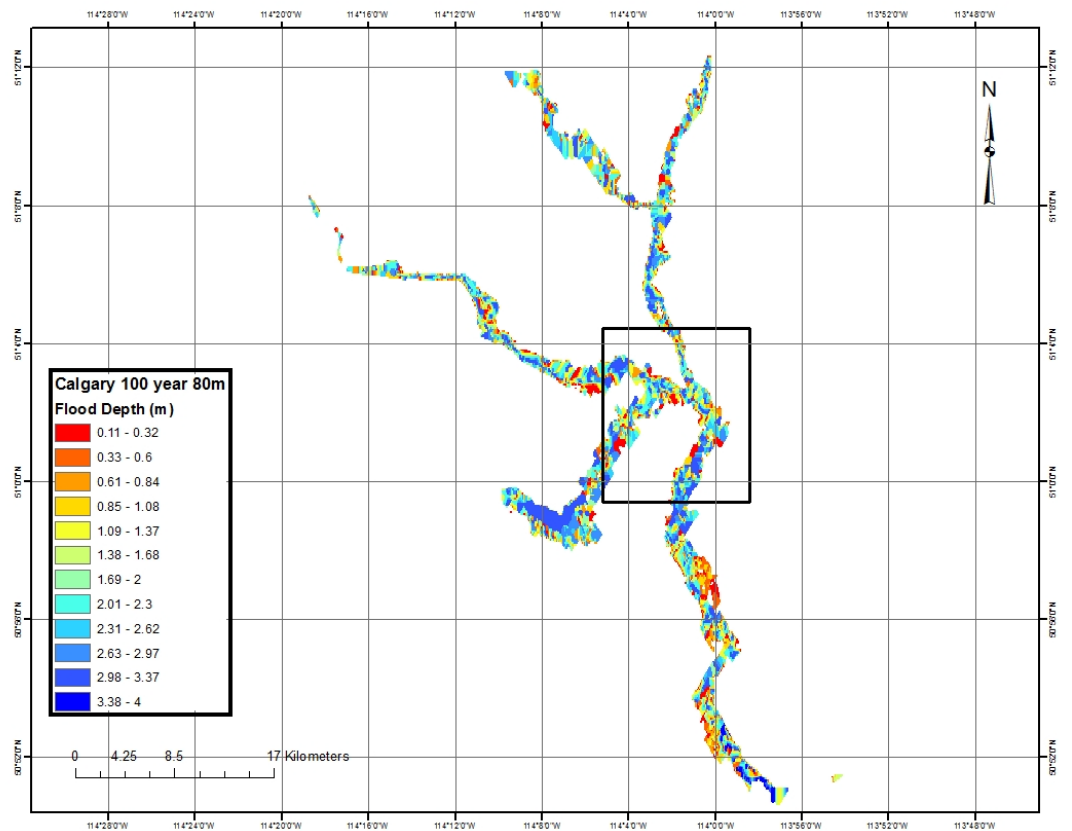
## Appendix C.5: 60m 100 year Floodplain Map



## Appendix C.6: 60m 200 year Floodplain Map

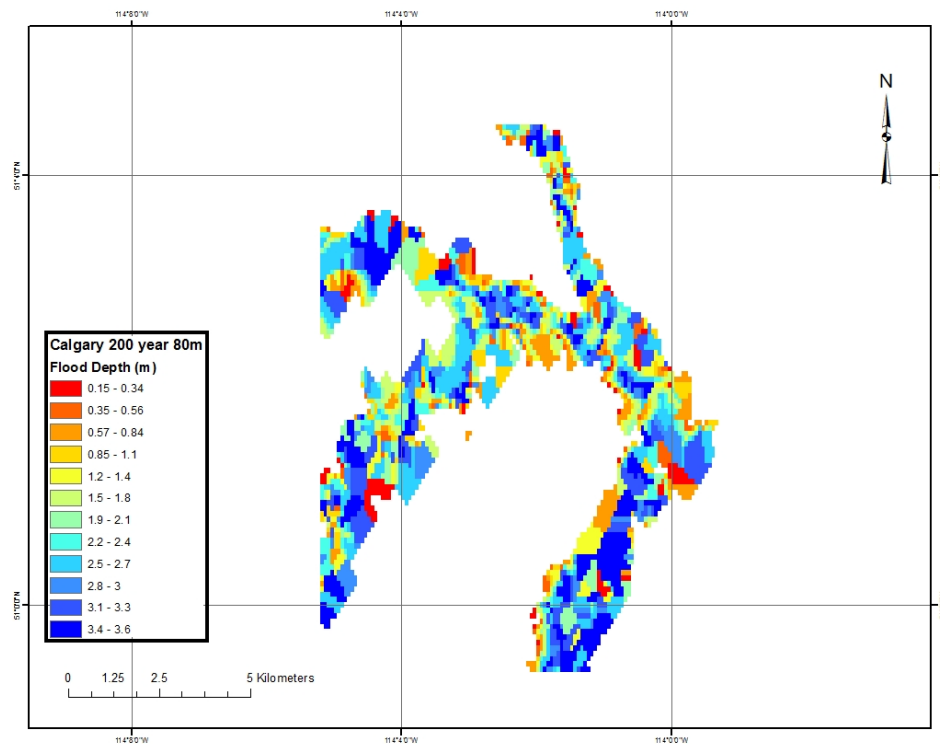
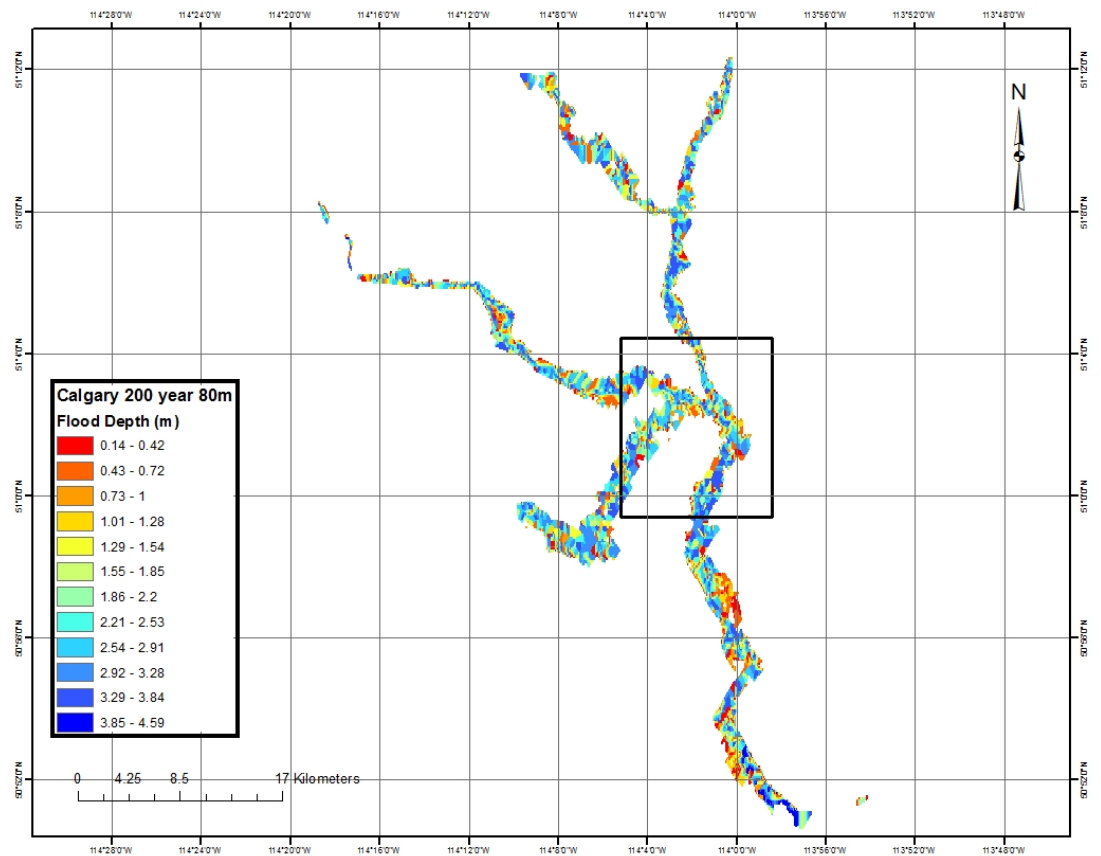


## Appendix C.7: 80m 100 year Floodplain Map

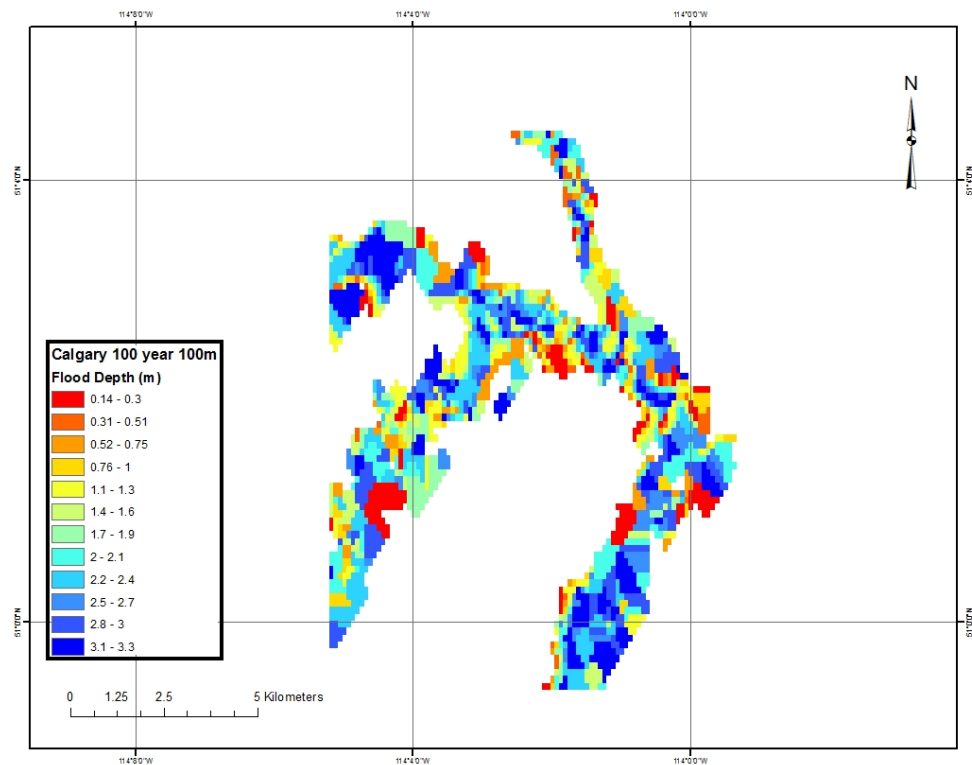
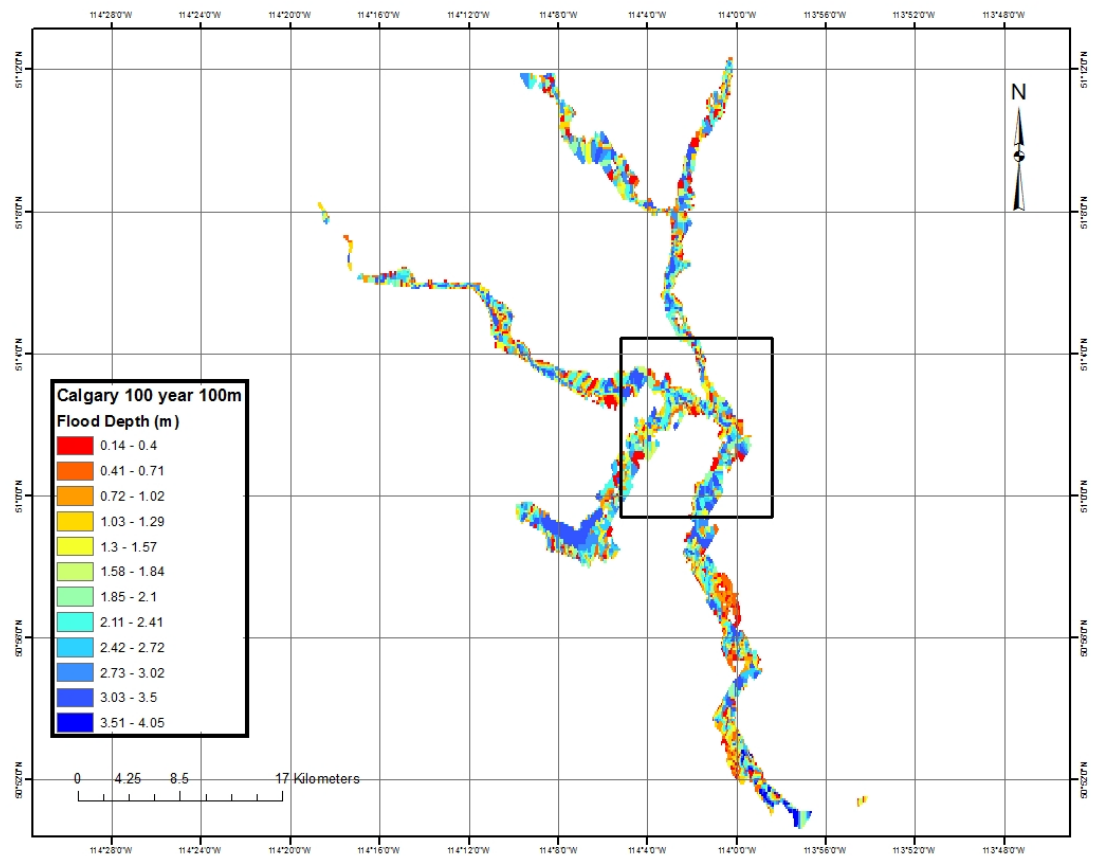




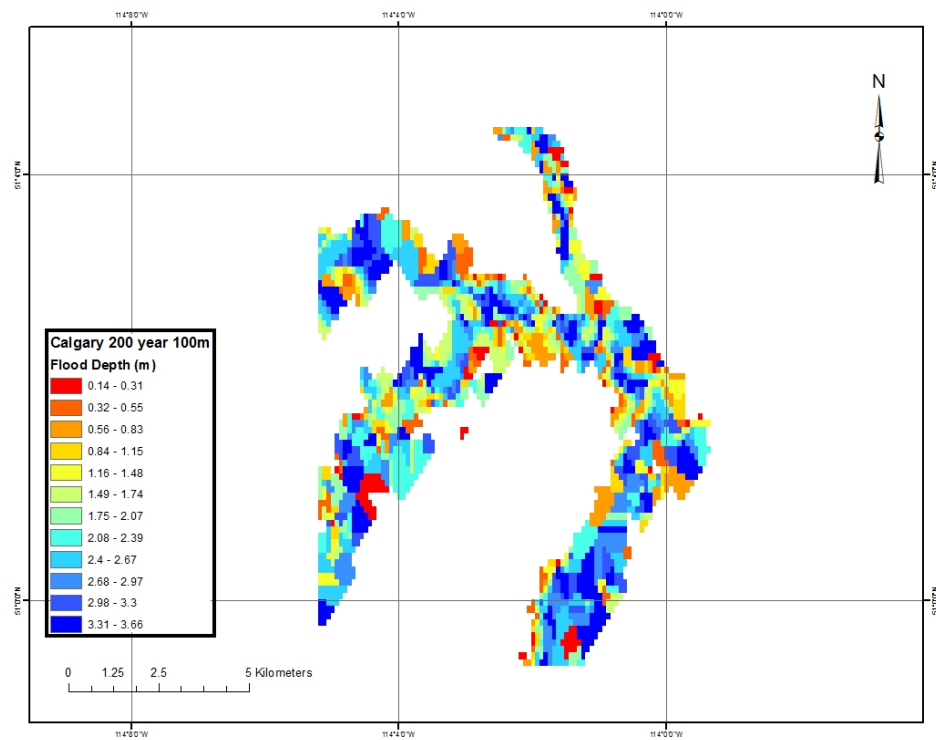
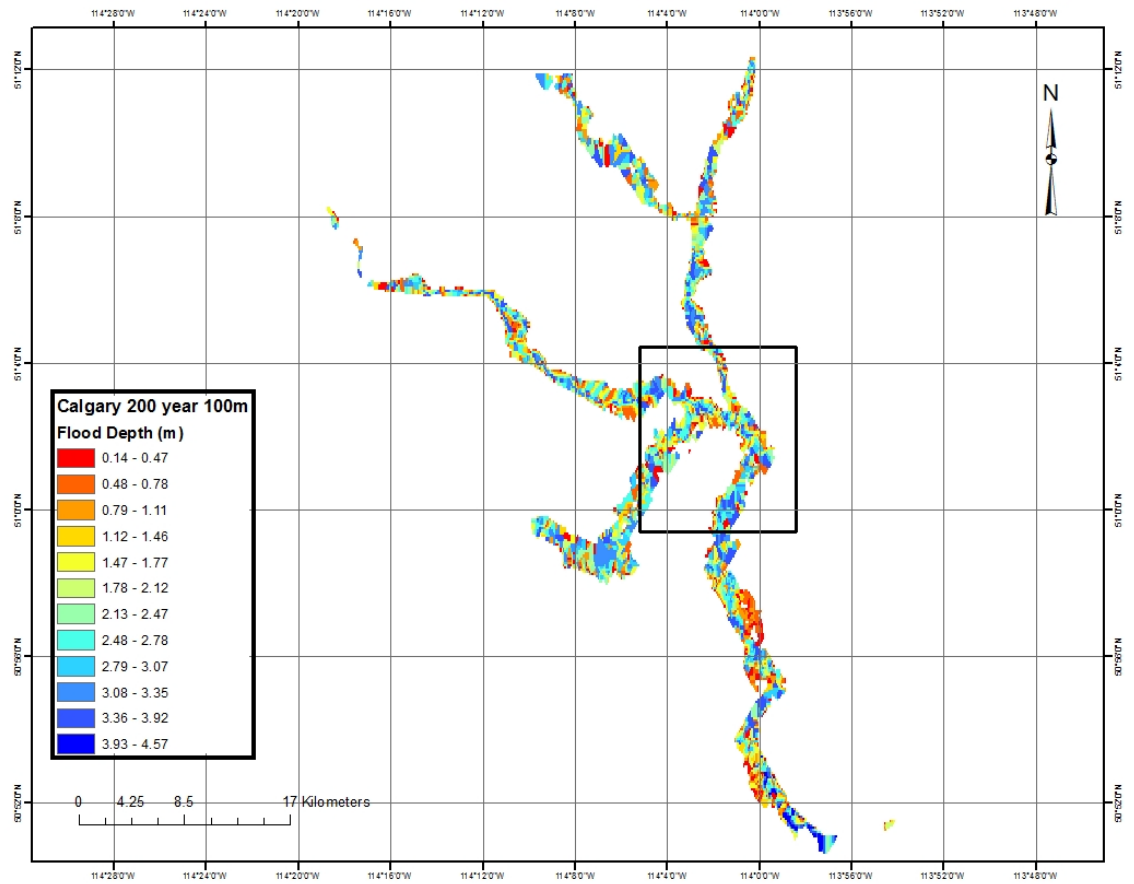
## Appendix C.8: 80m 200 year Floodplain Map



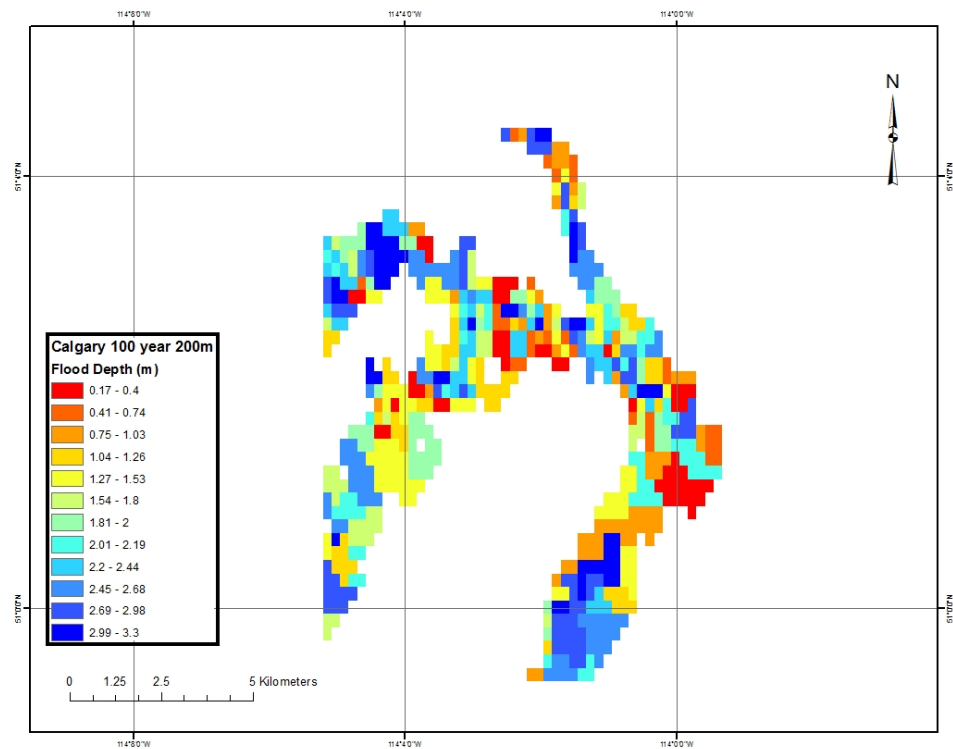
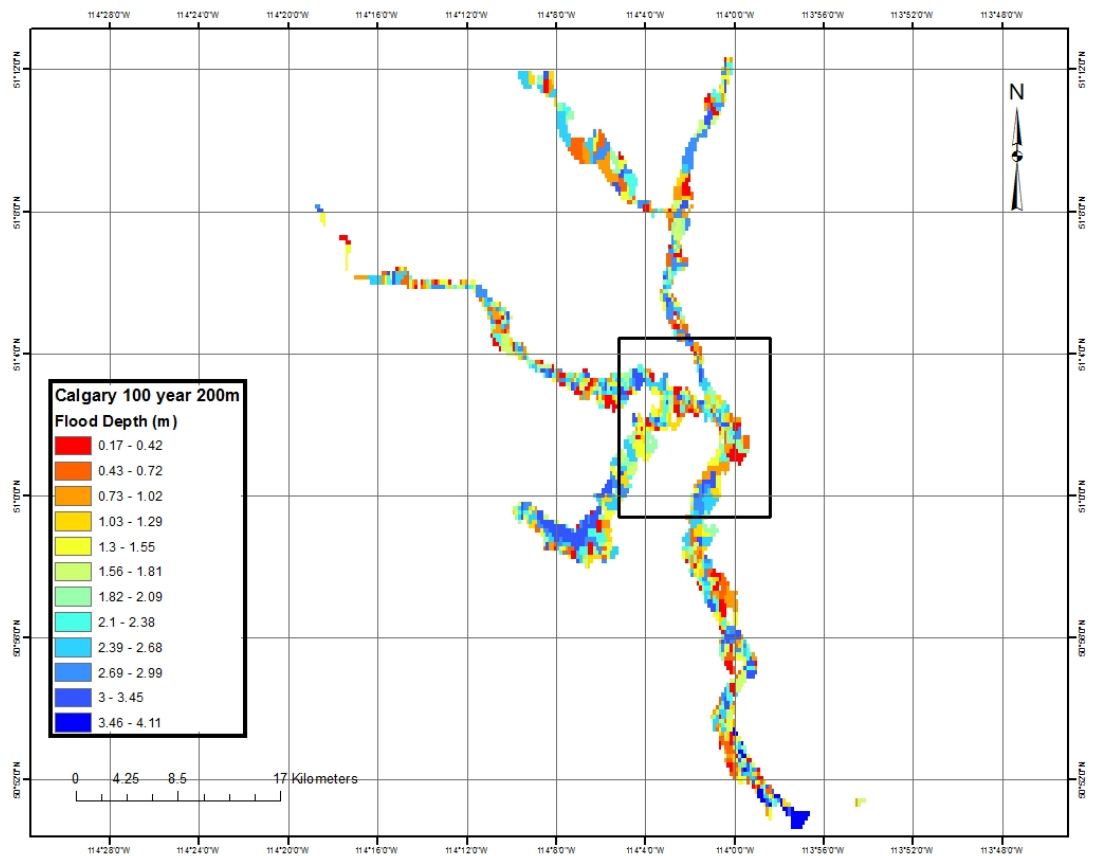
## Appendix C.9: 100m 100 year Floodplain Map



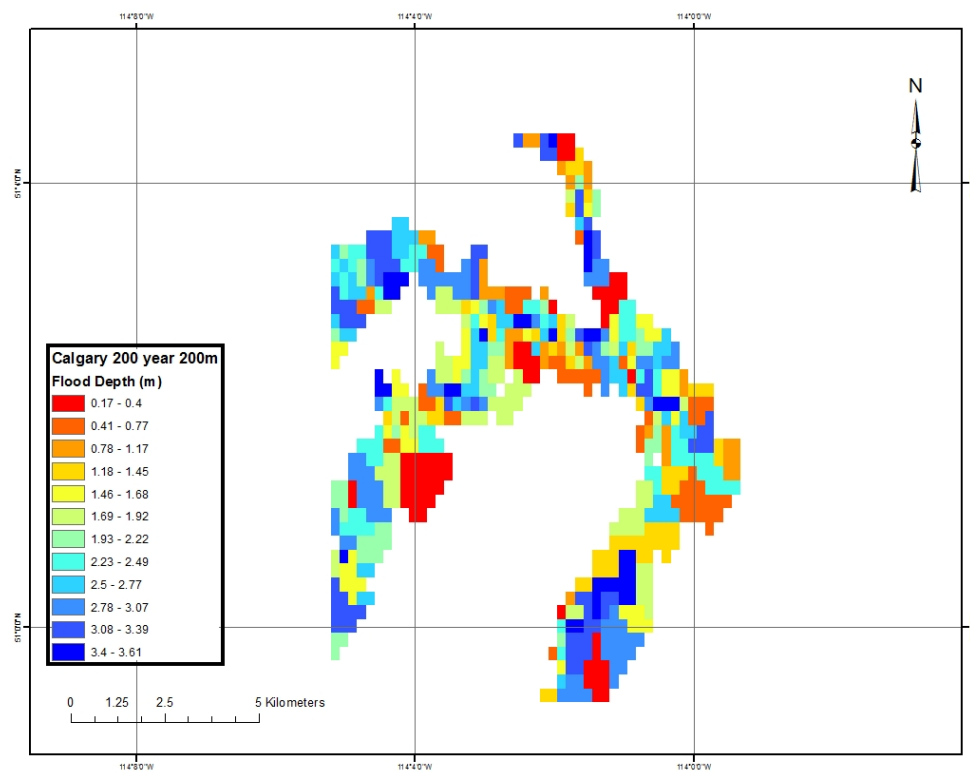
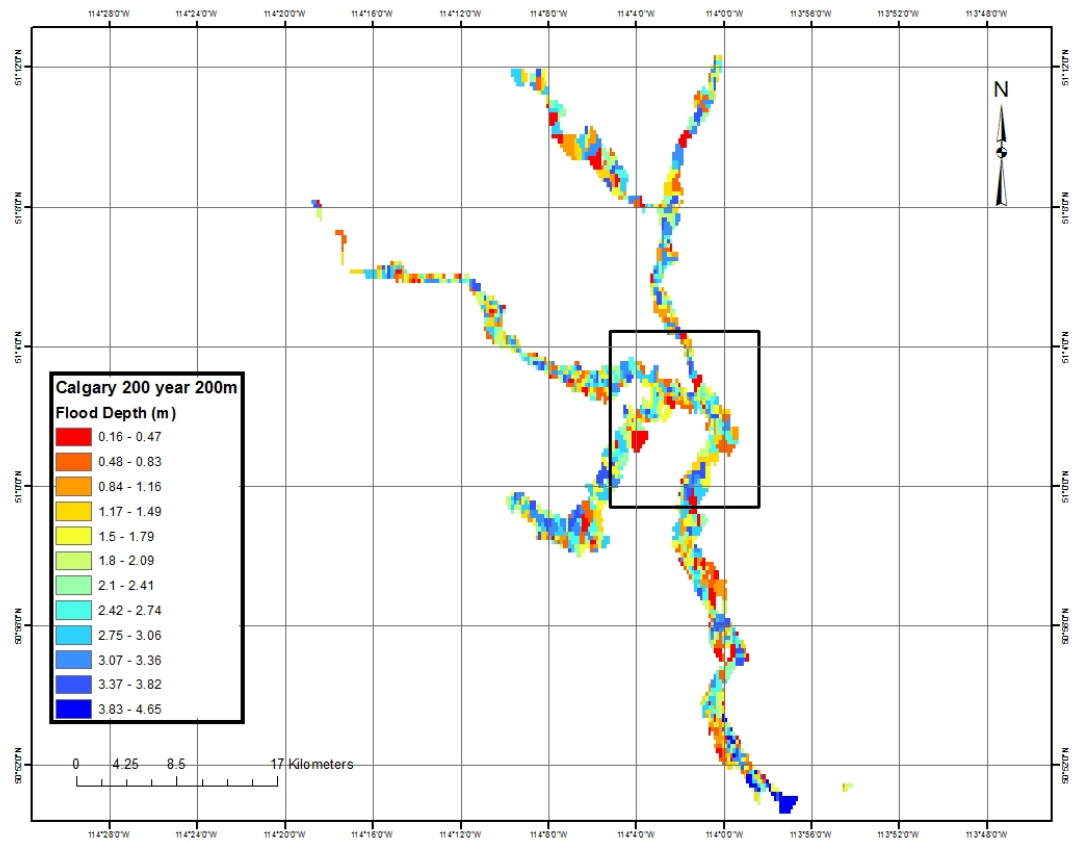
## Appendix C.10: 100m 200 year Floodplain Map



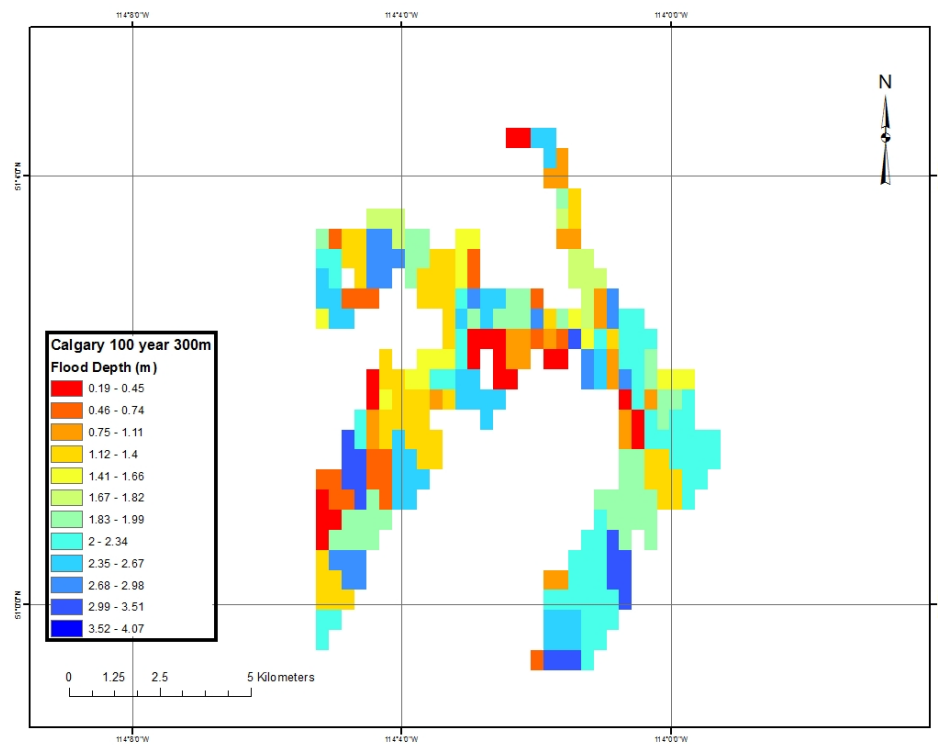
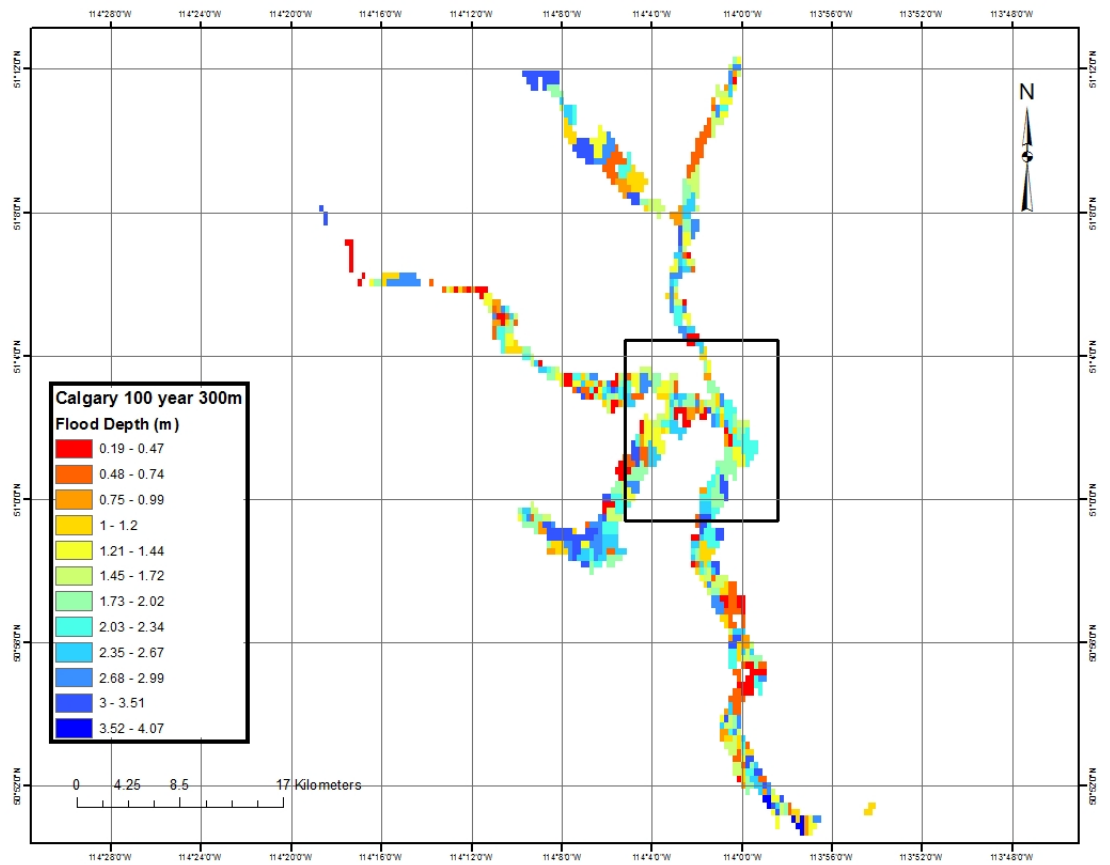
## Appendix C.11: 200m 100 year Floodplain Map



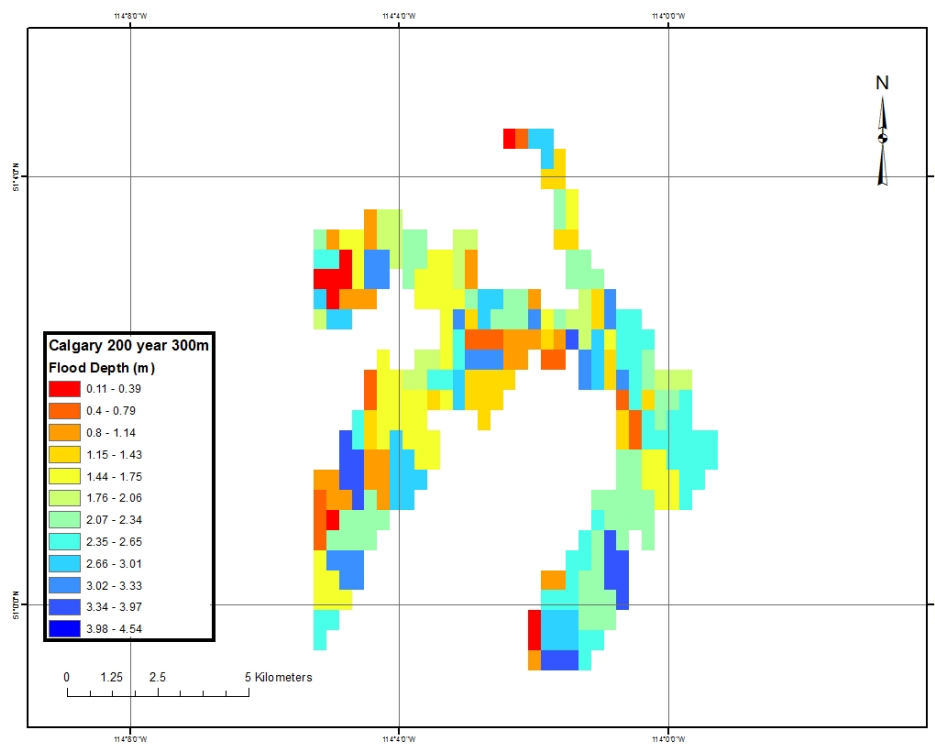
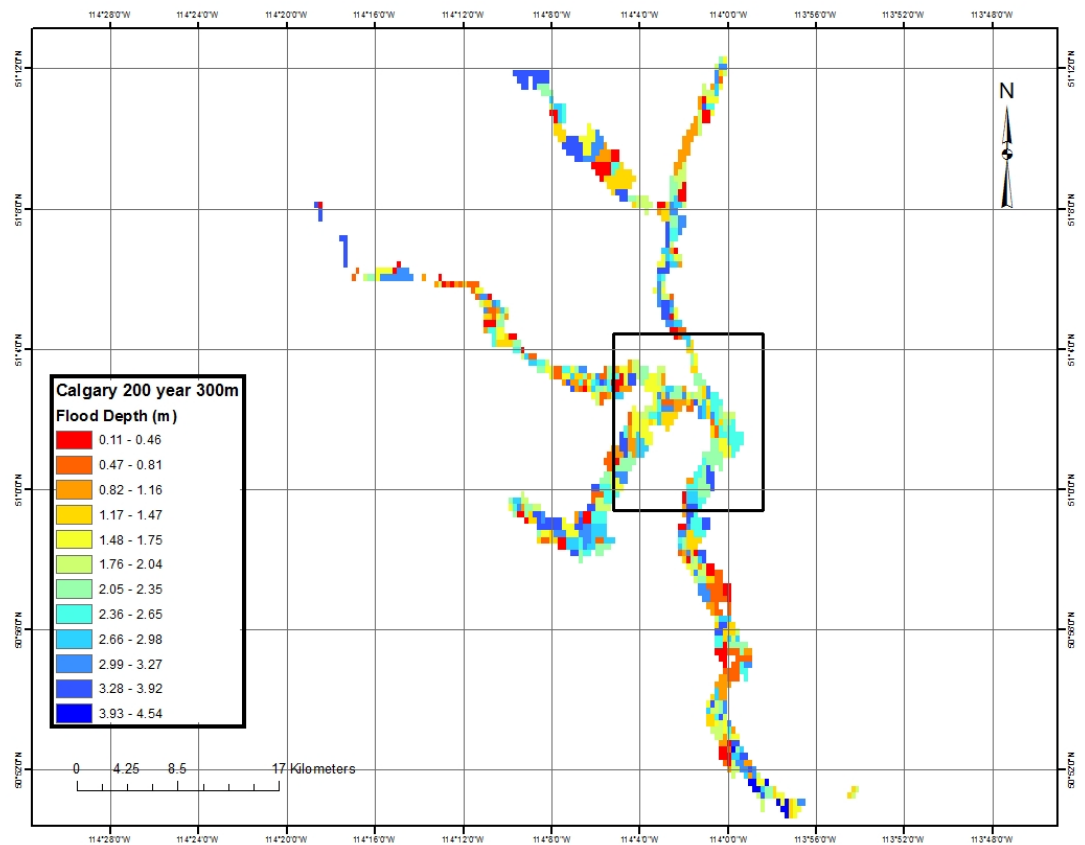
## Appendix C.12: 200m 200 year Floodplain Map



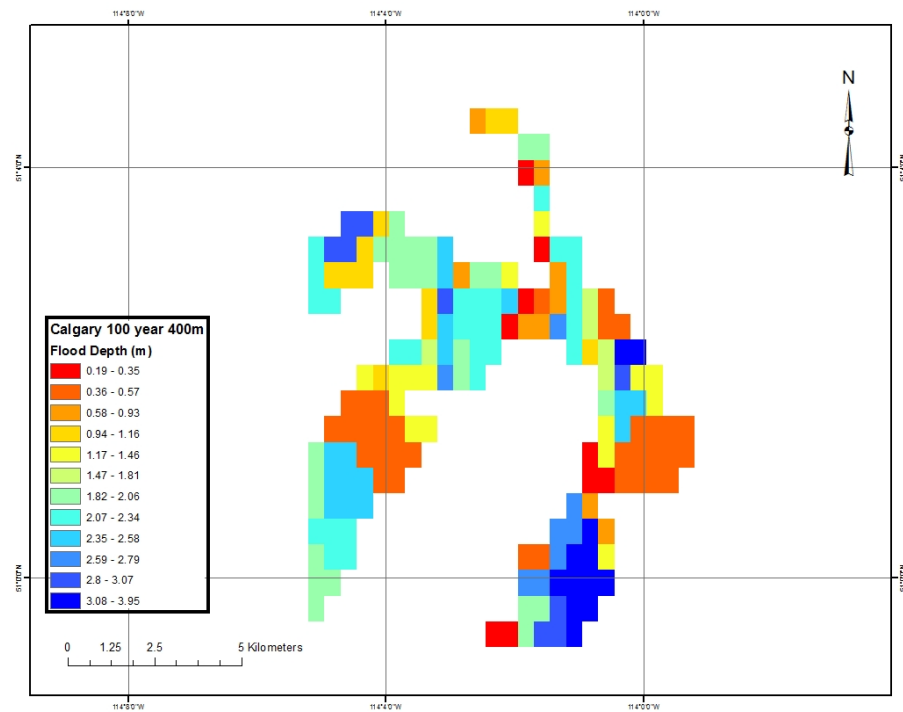
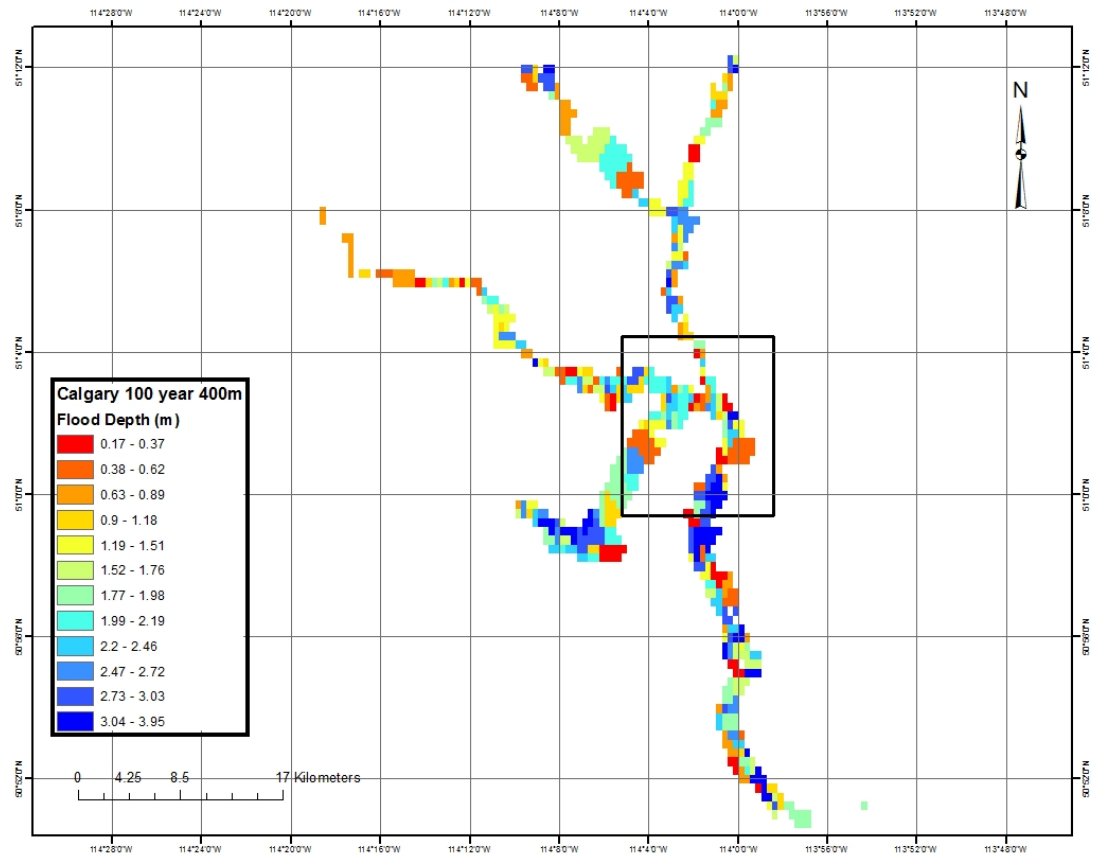
## Appendix C.13: 300m 100 year Floodplain Map



## Appendix C.14: 300m 200 year Floodplain Map

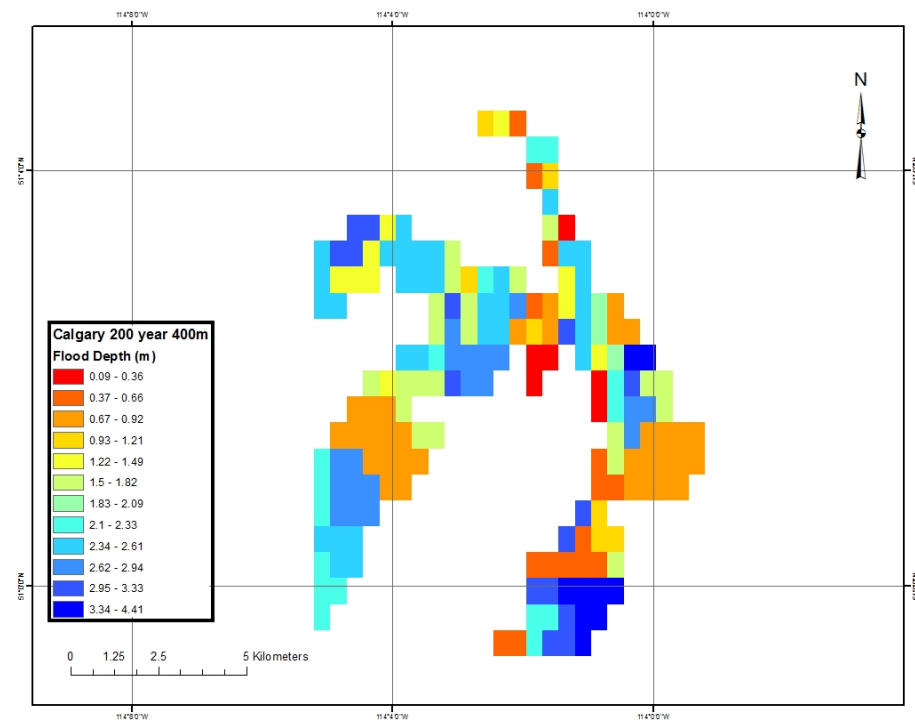
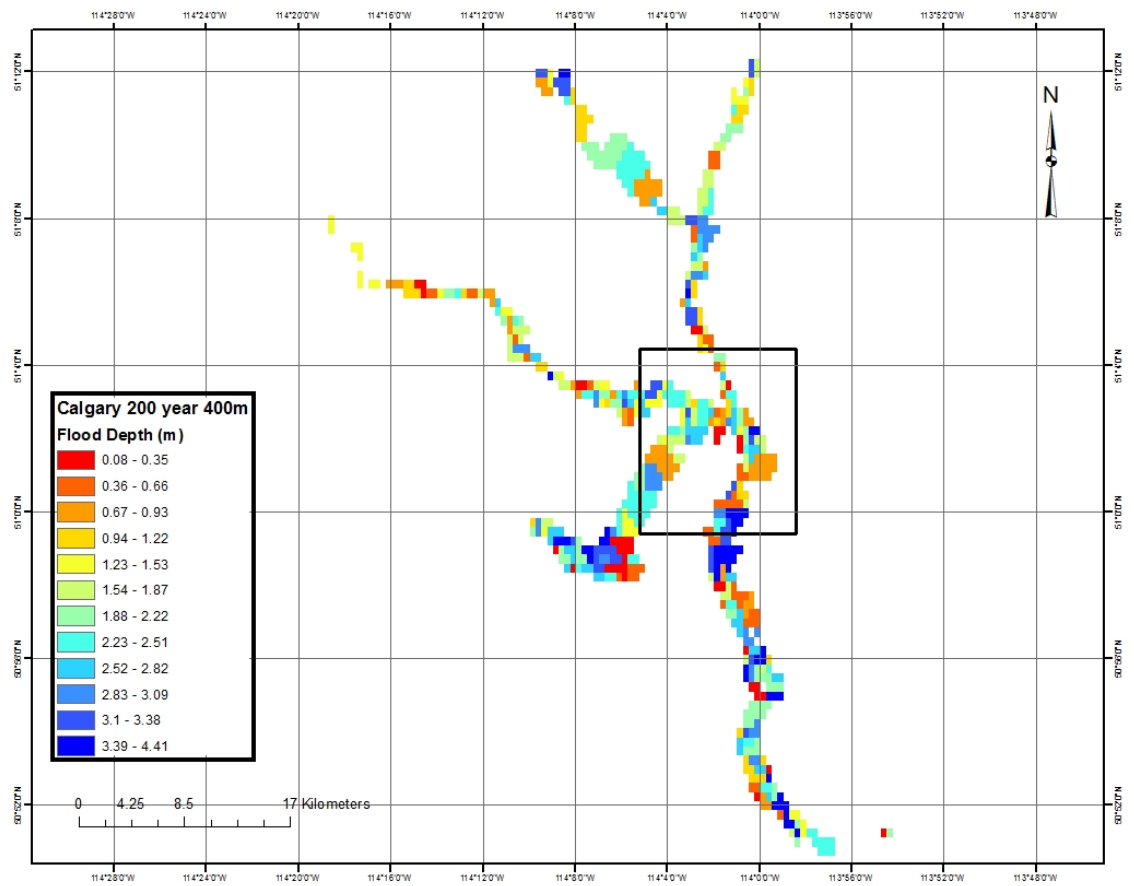


## Appendix C.15: 400m 100 year Floodplain Map



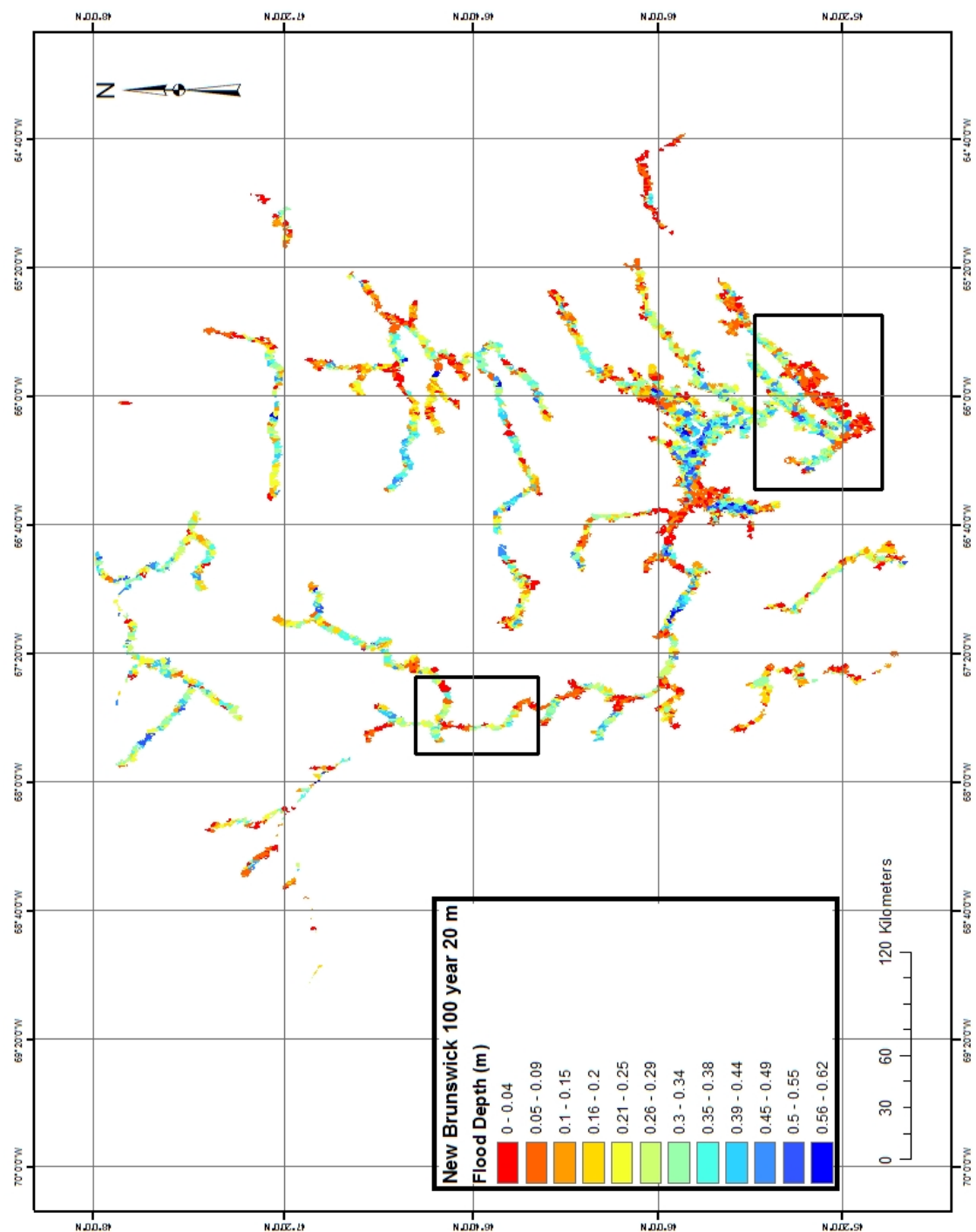


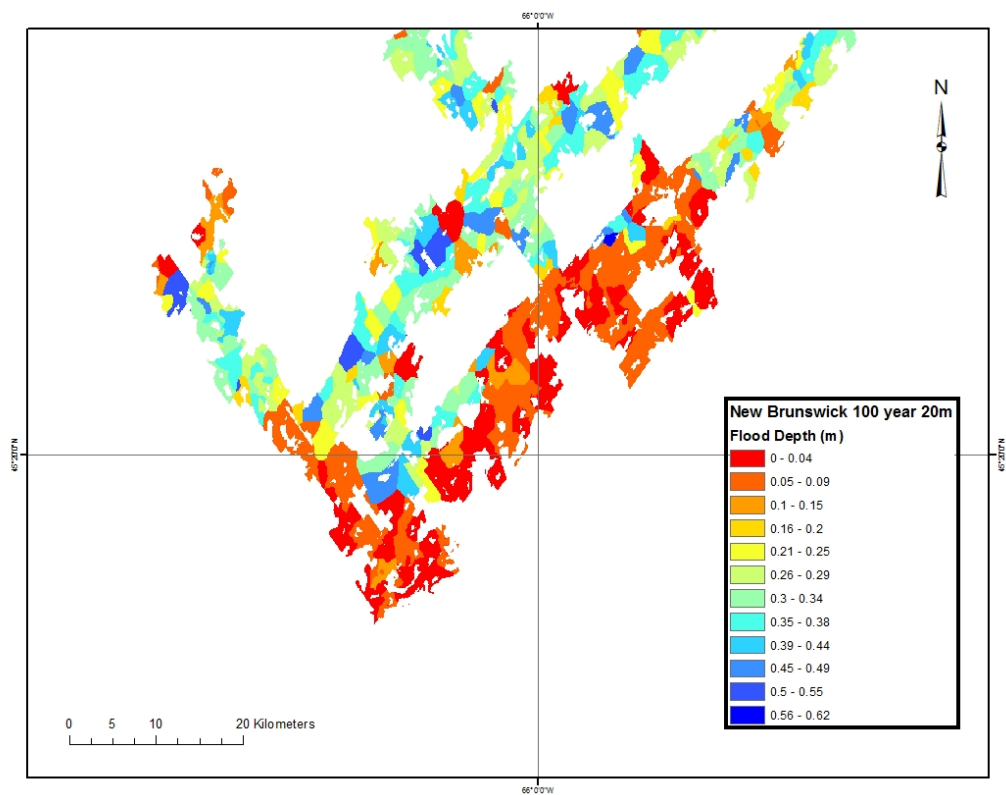
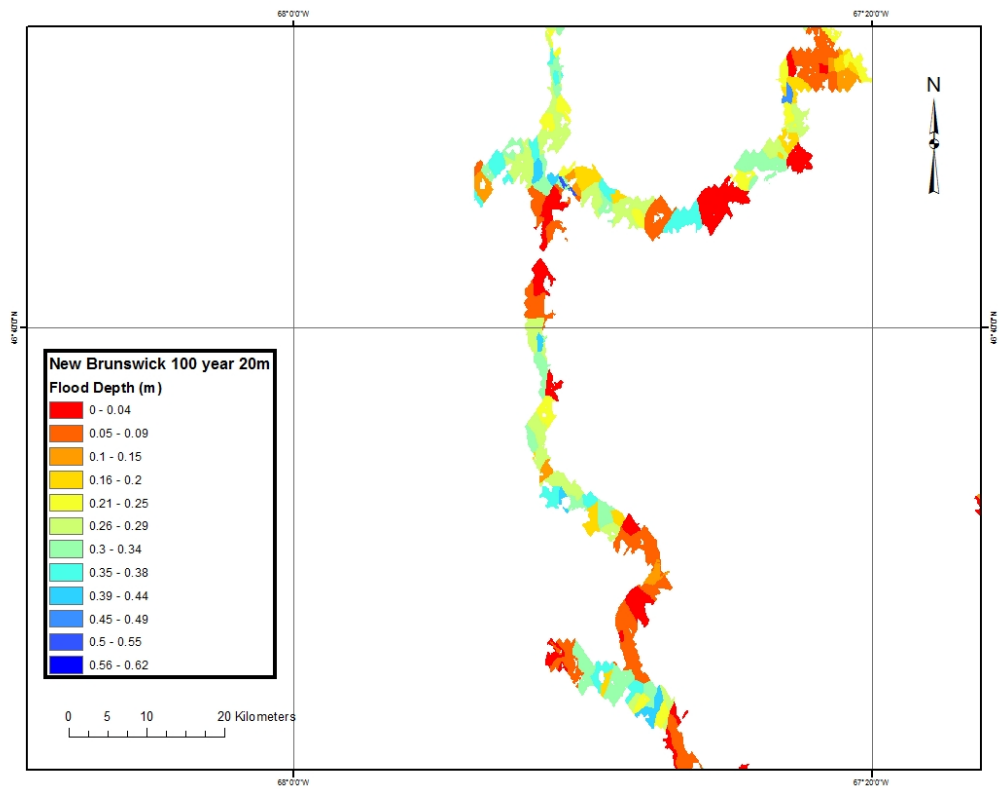
## Appendix C.16: 400m 200 year Floodplain Map



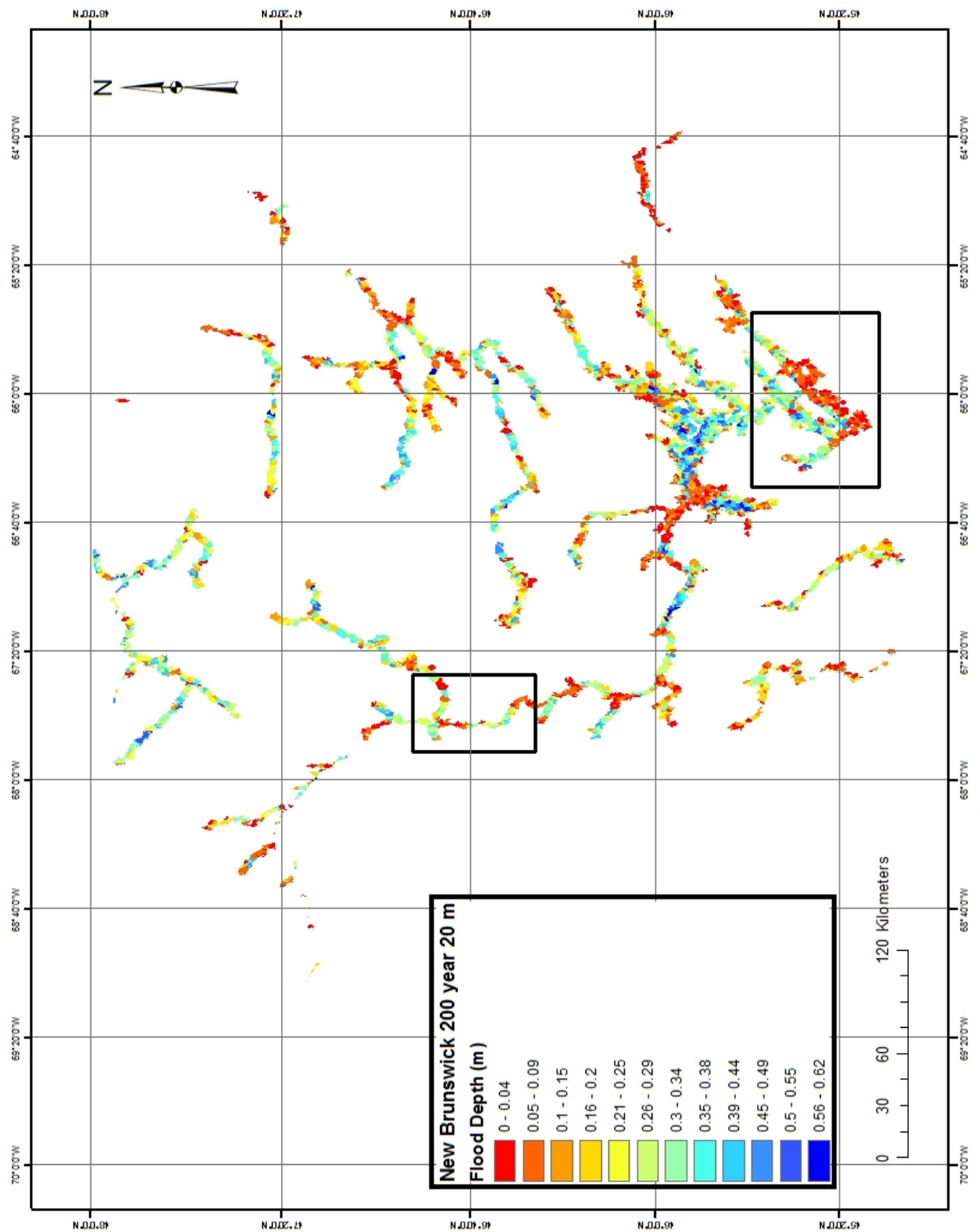
## Appendix D: New Brunswick Floodplain Maps

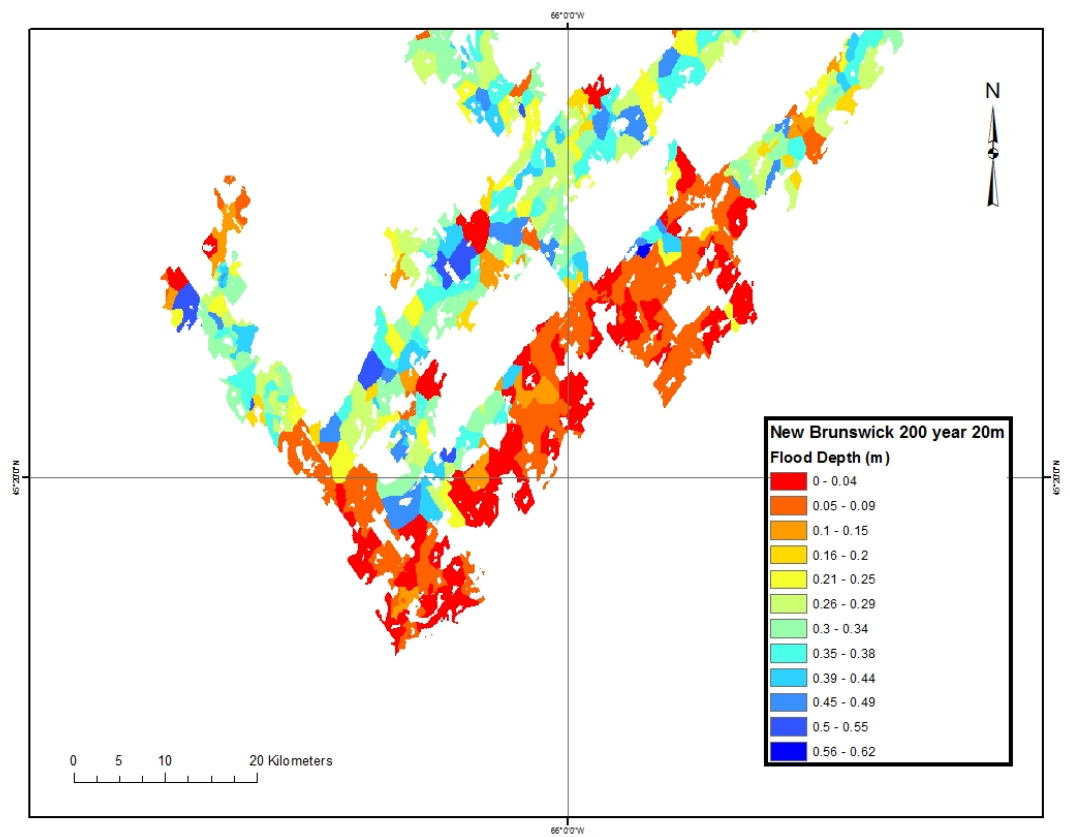
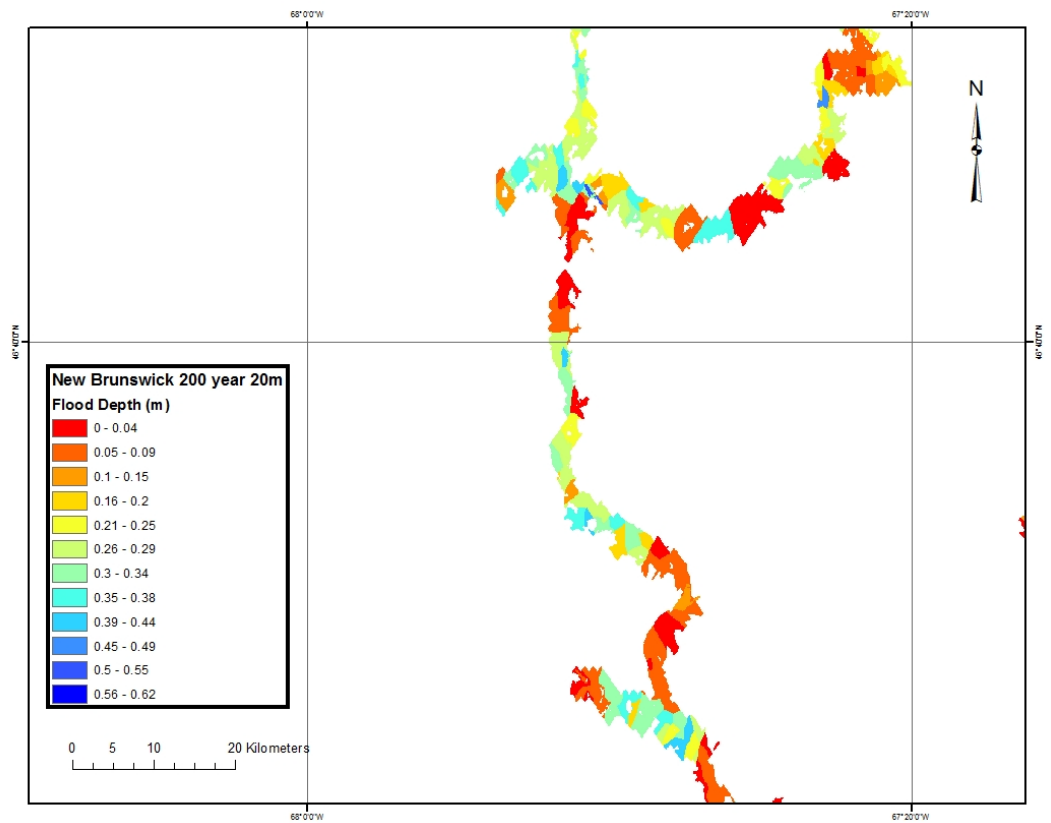
### Appendix D.1: 20m 100 year Floodplain Map



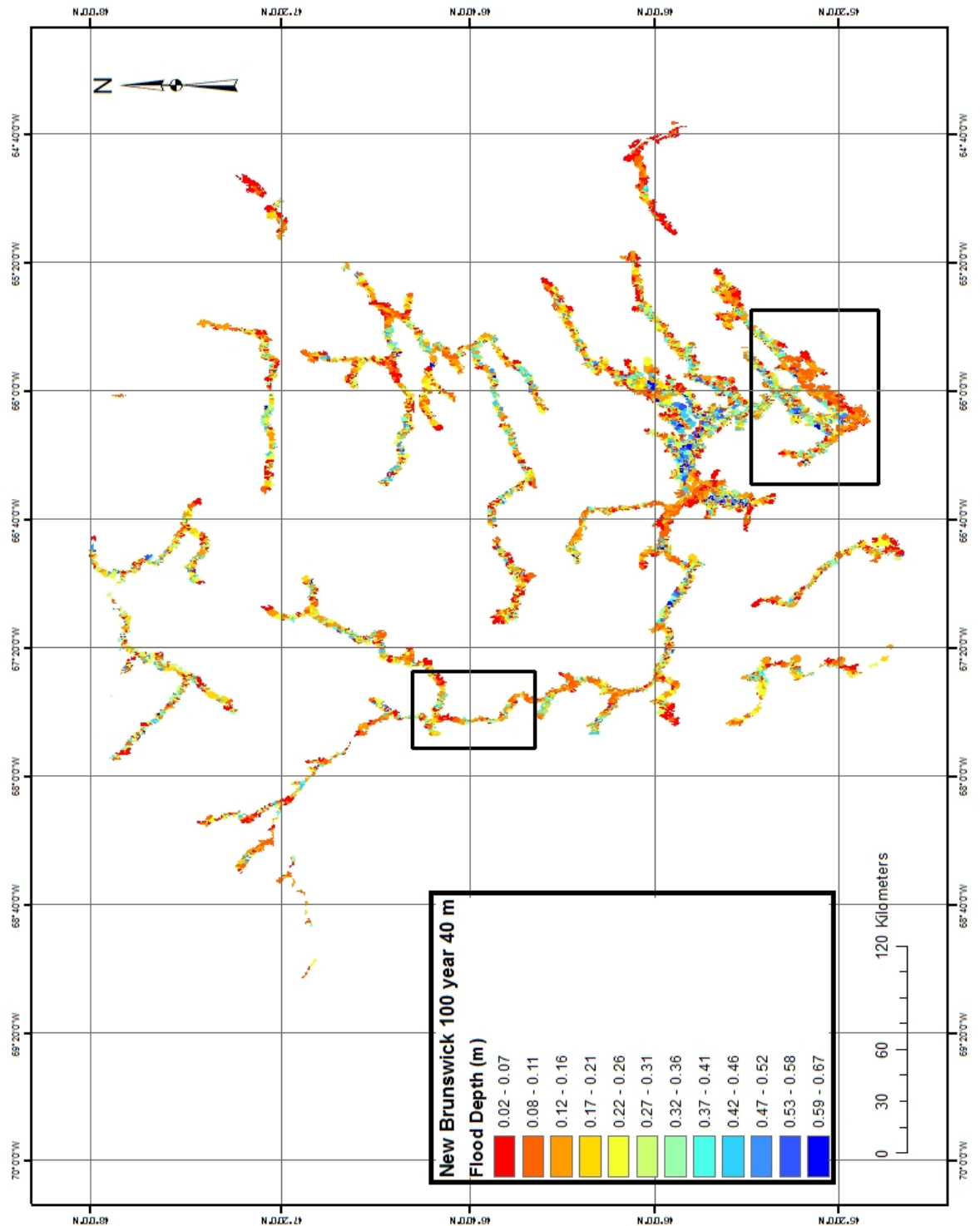


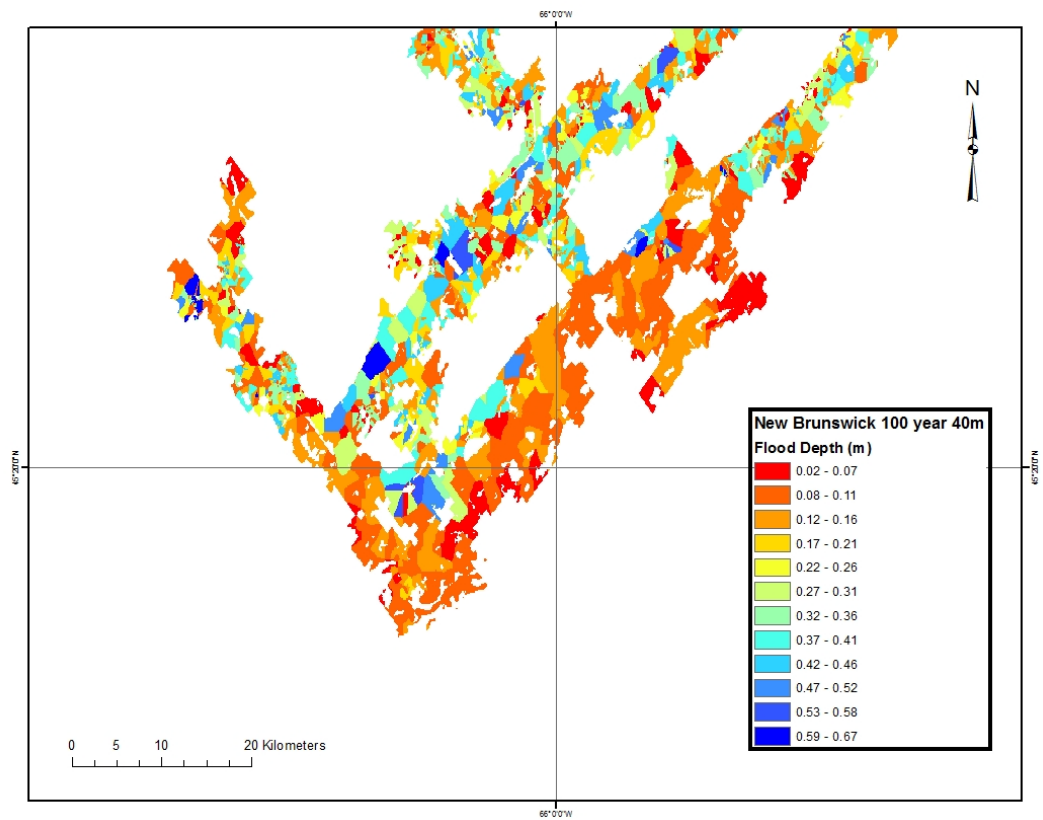
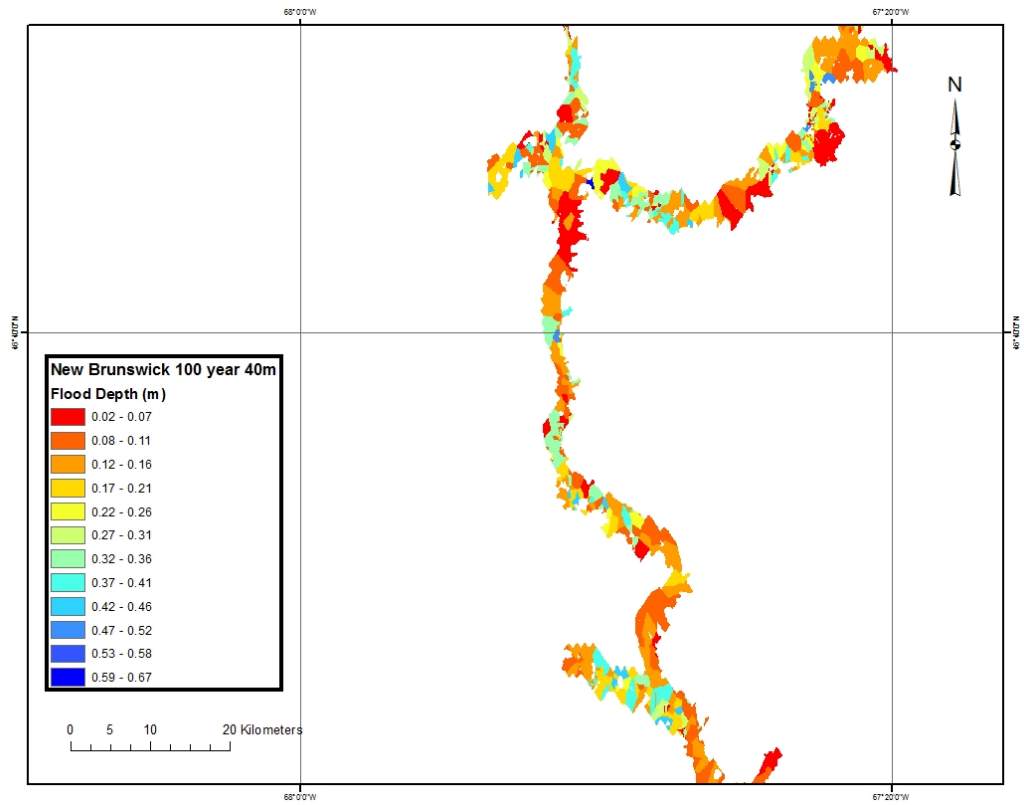
## Appendix D.2: 20m 200 year Floodplain Map



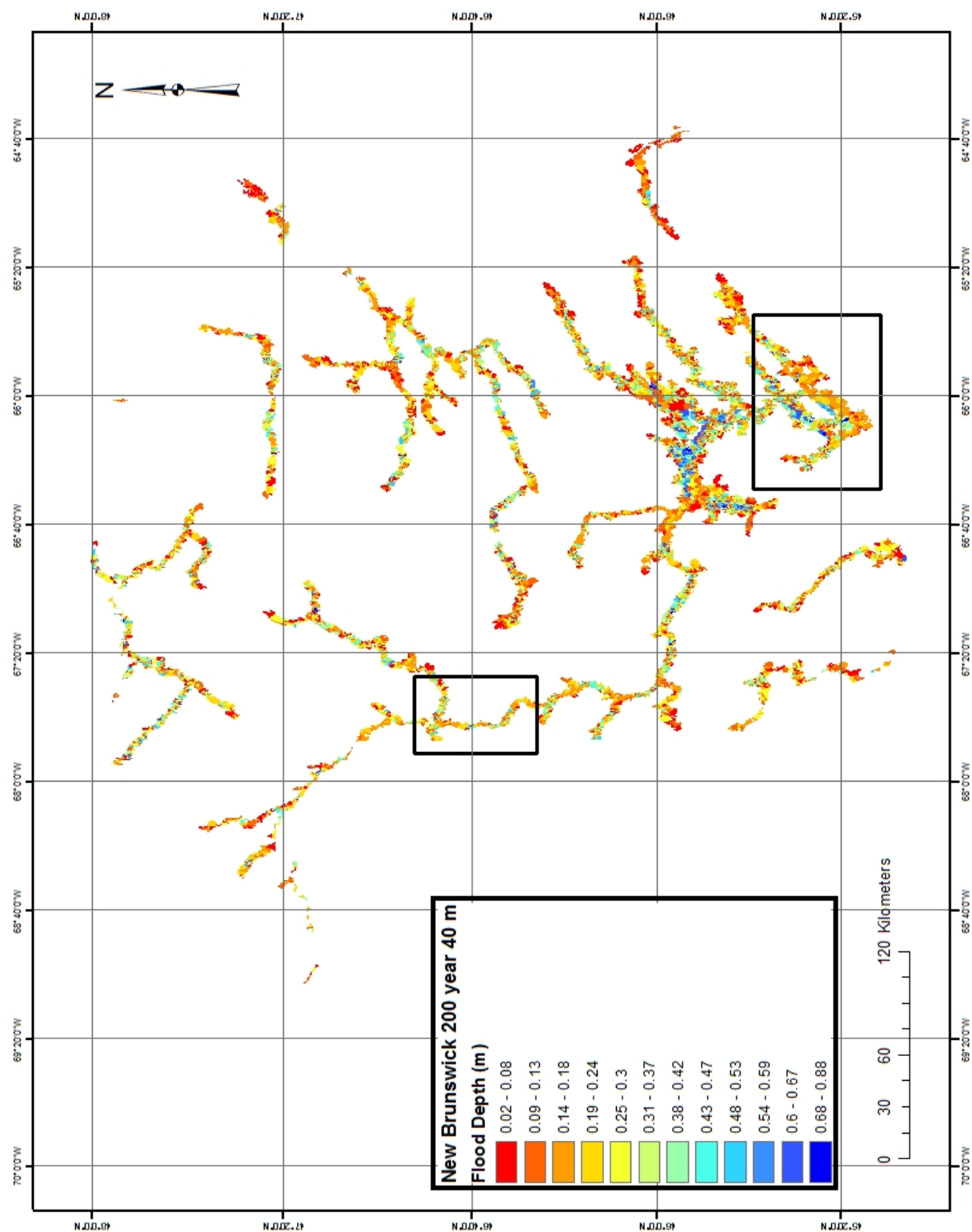


## Appendix D.3: 40m 100 year Floodplain Map

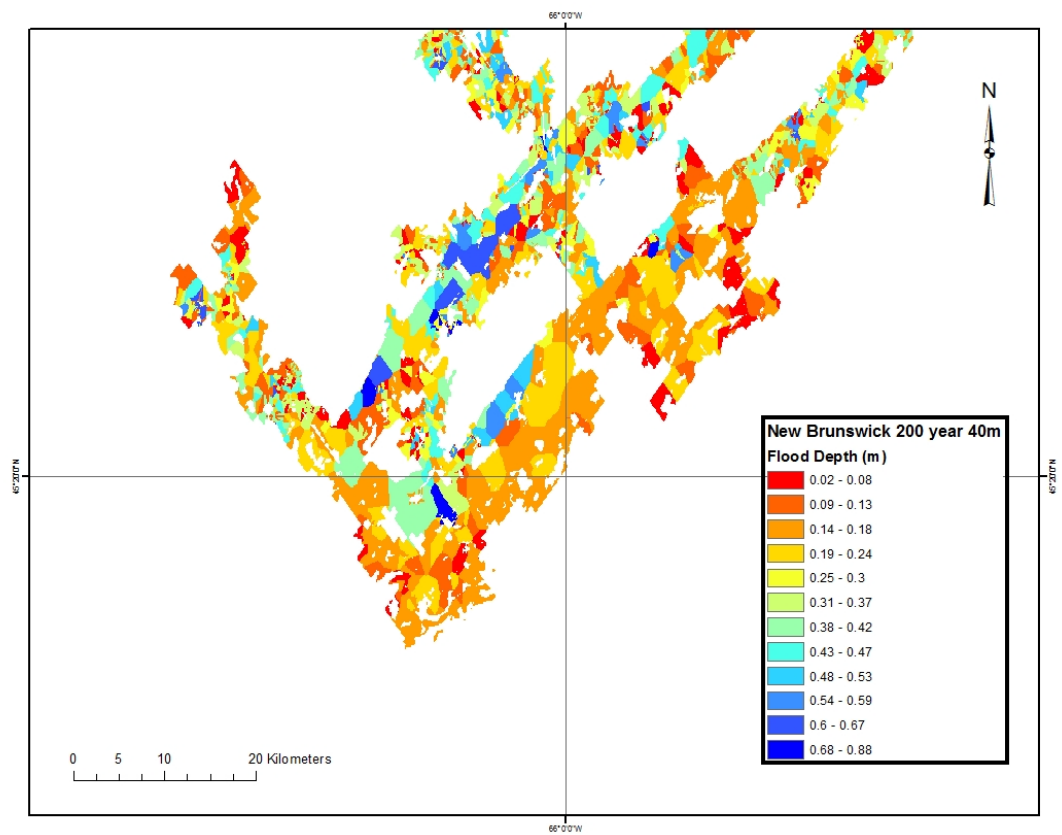
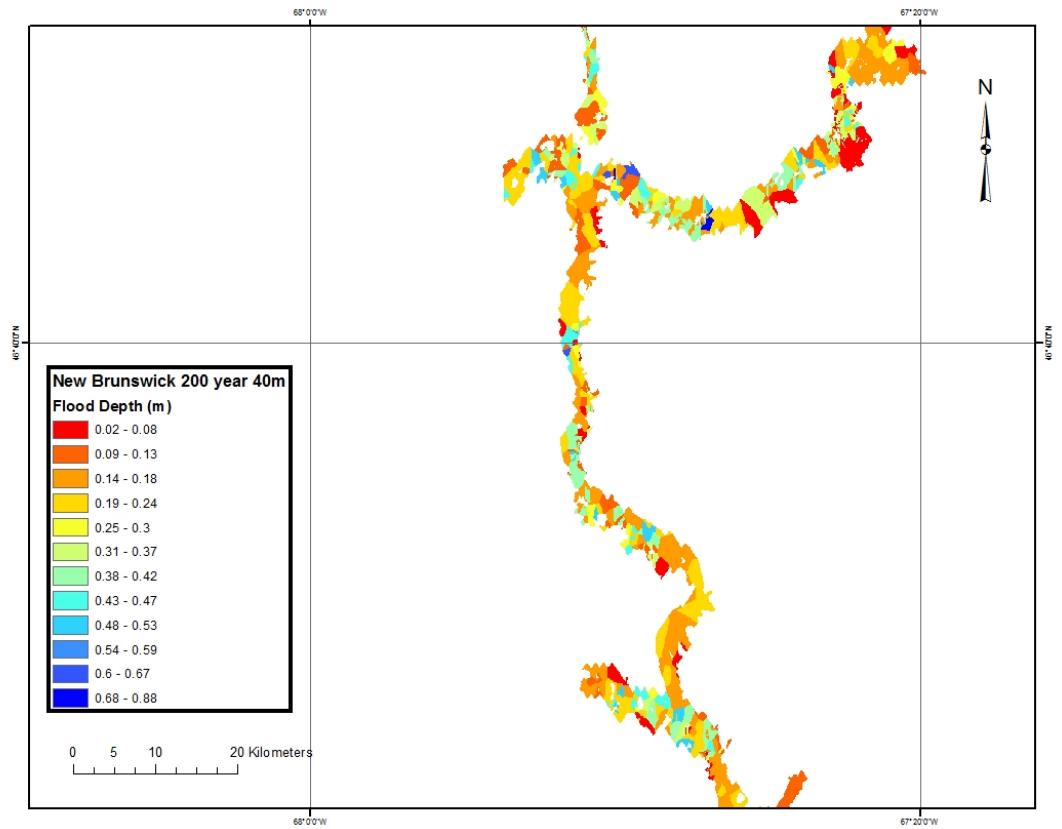




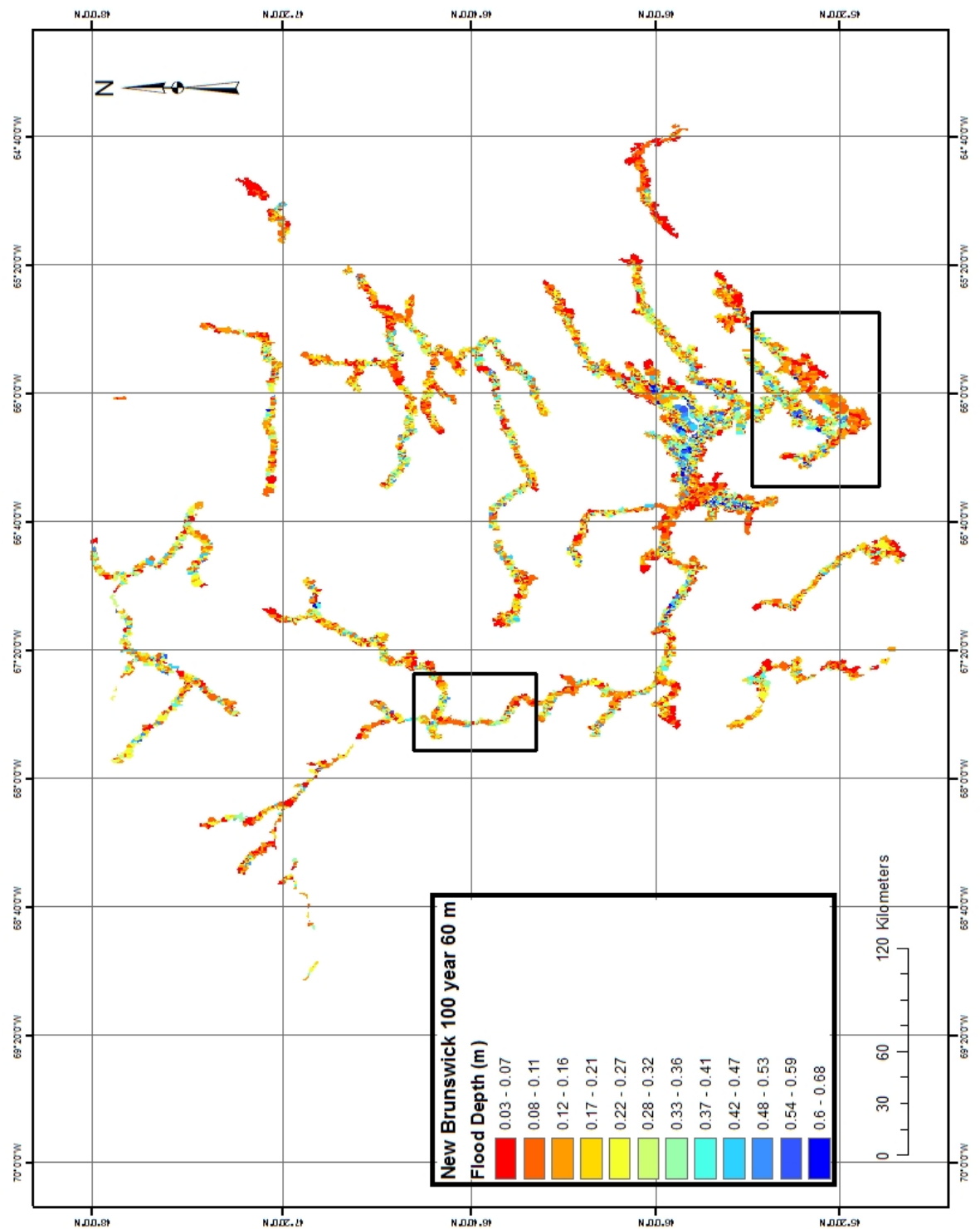
Appendix D.4: 40m 200 year Floodplain Map

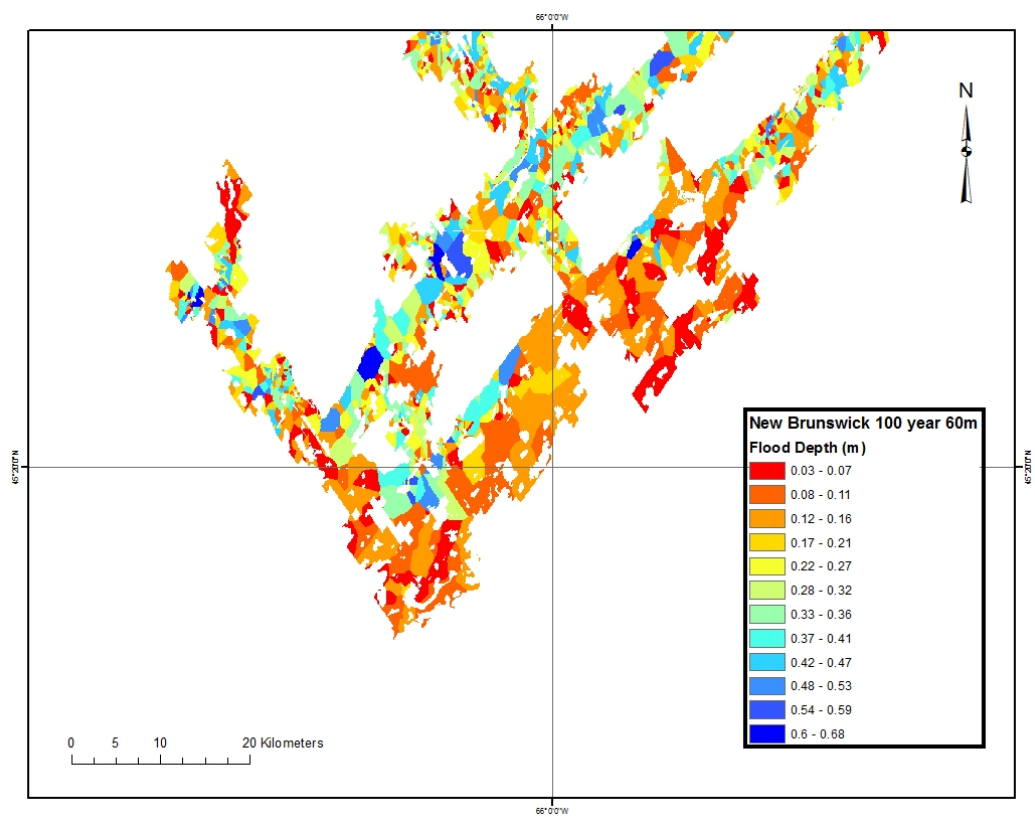
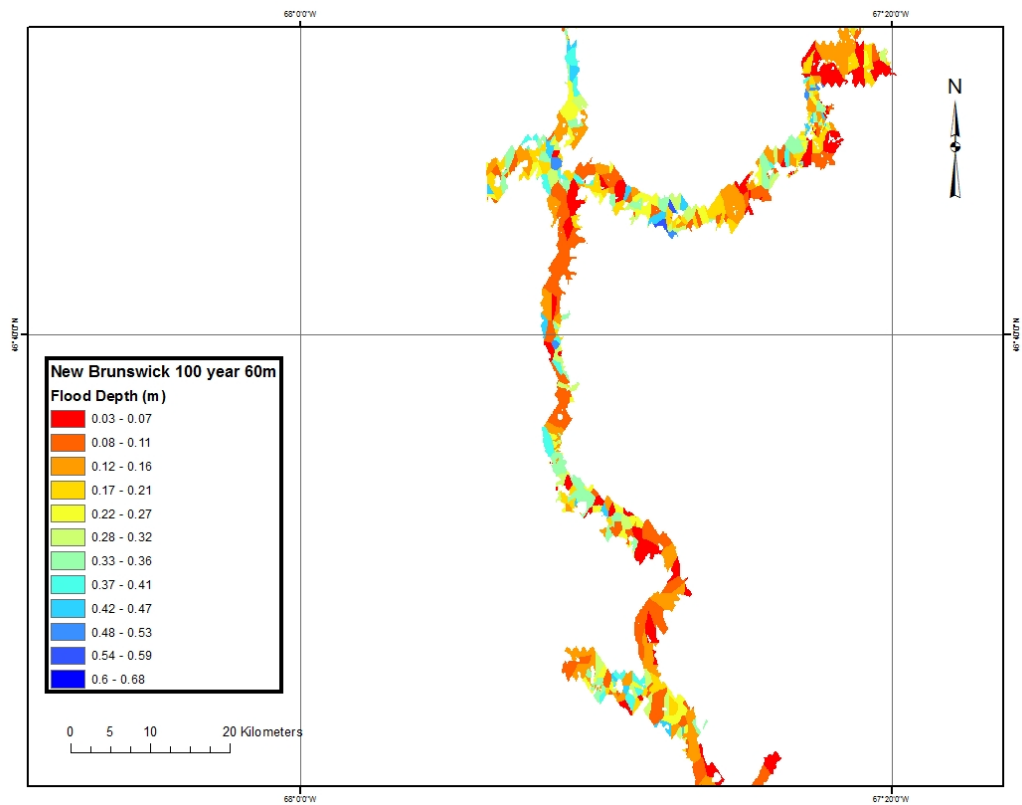




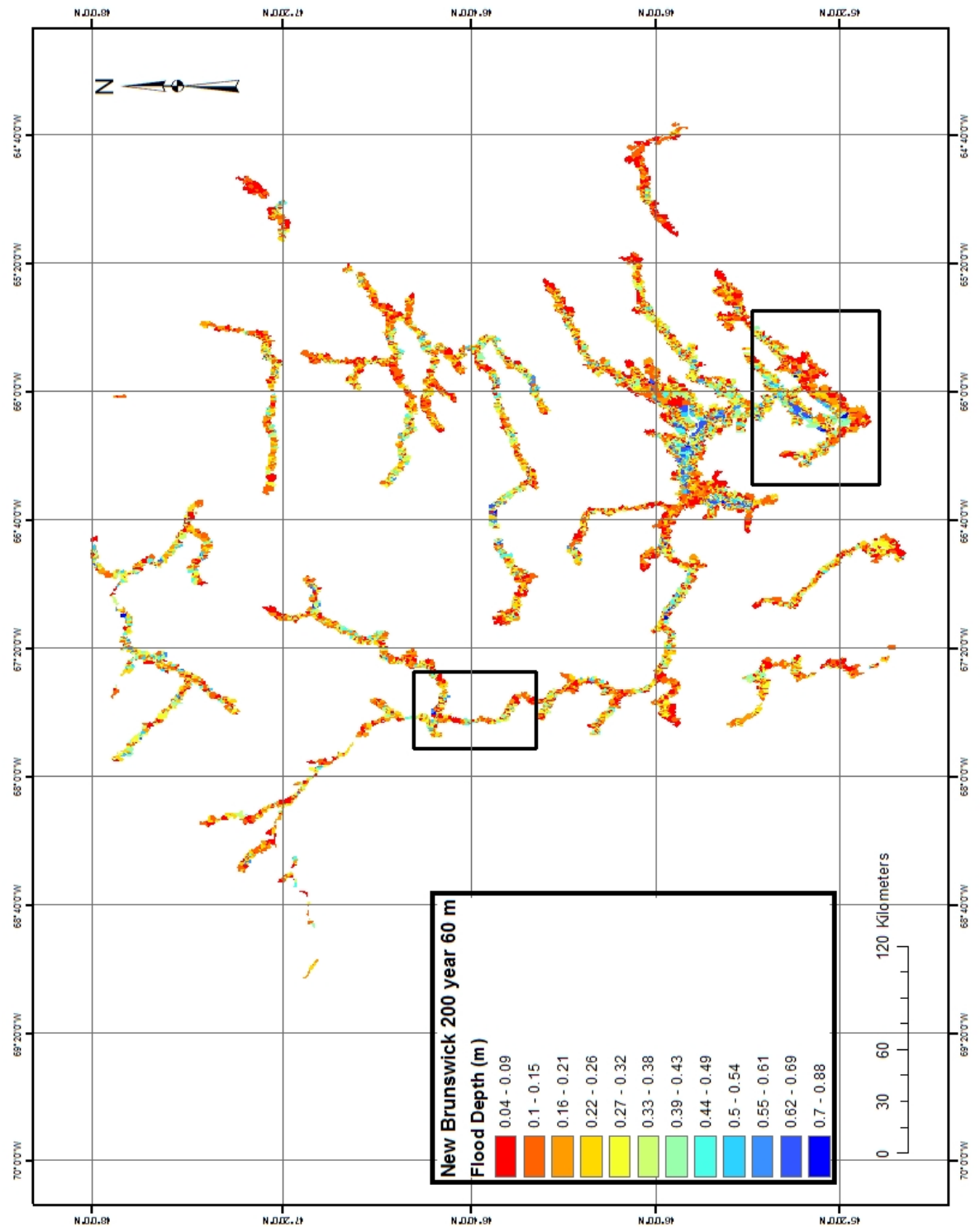


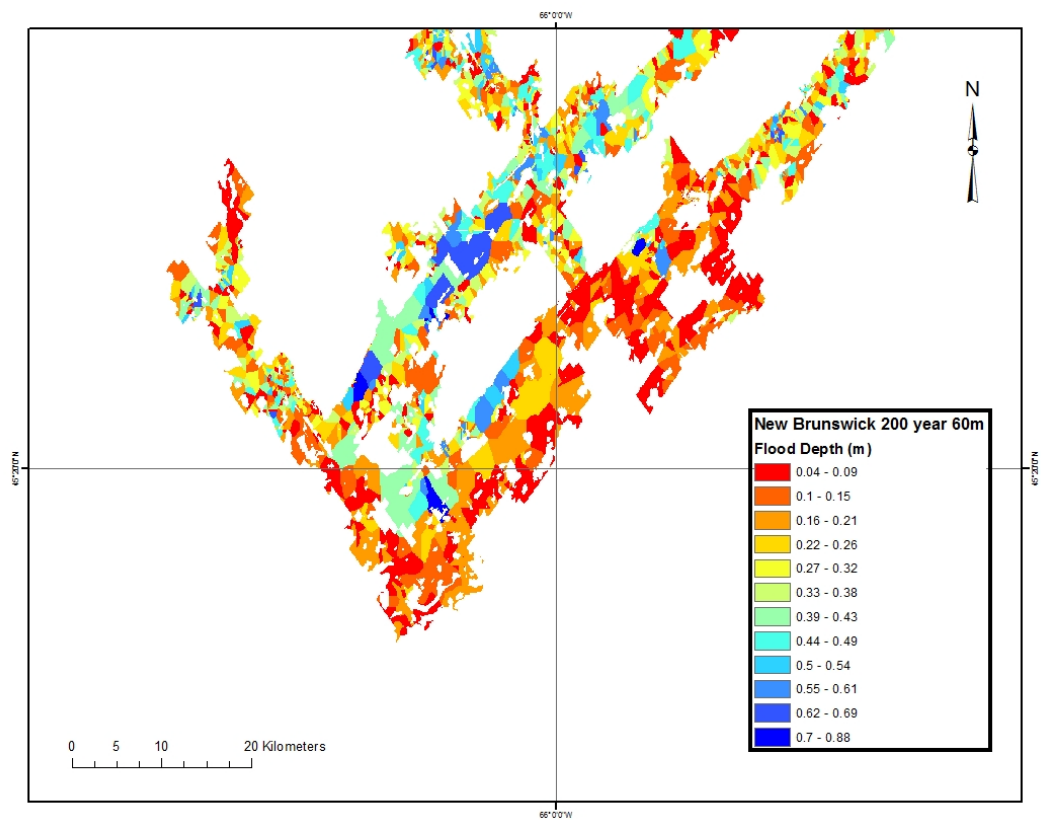
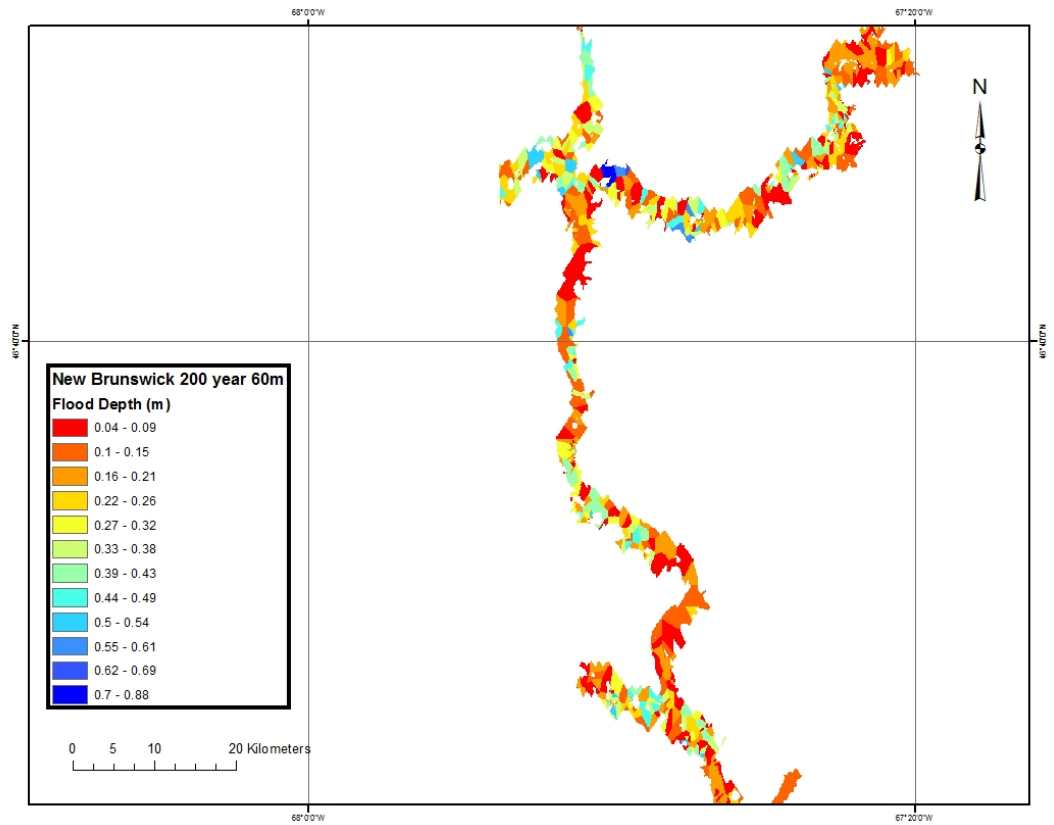
## Appendix D.5: 60m 100 year Floodplain Map



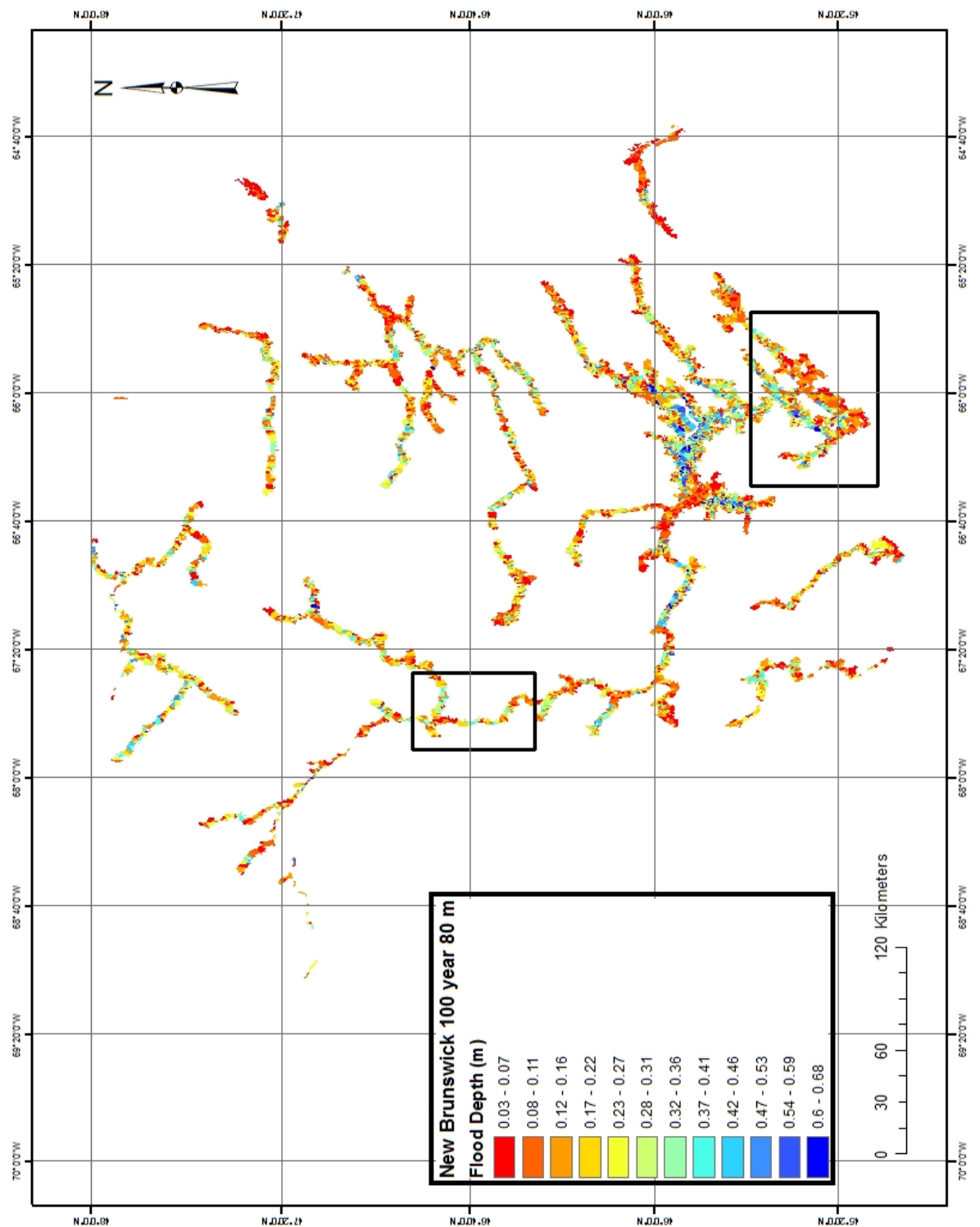


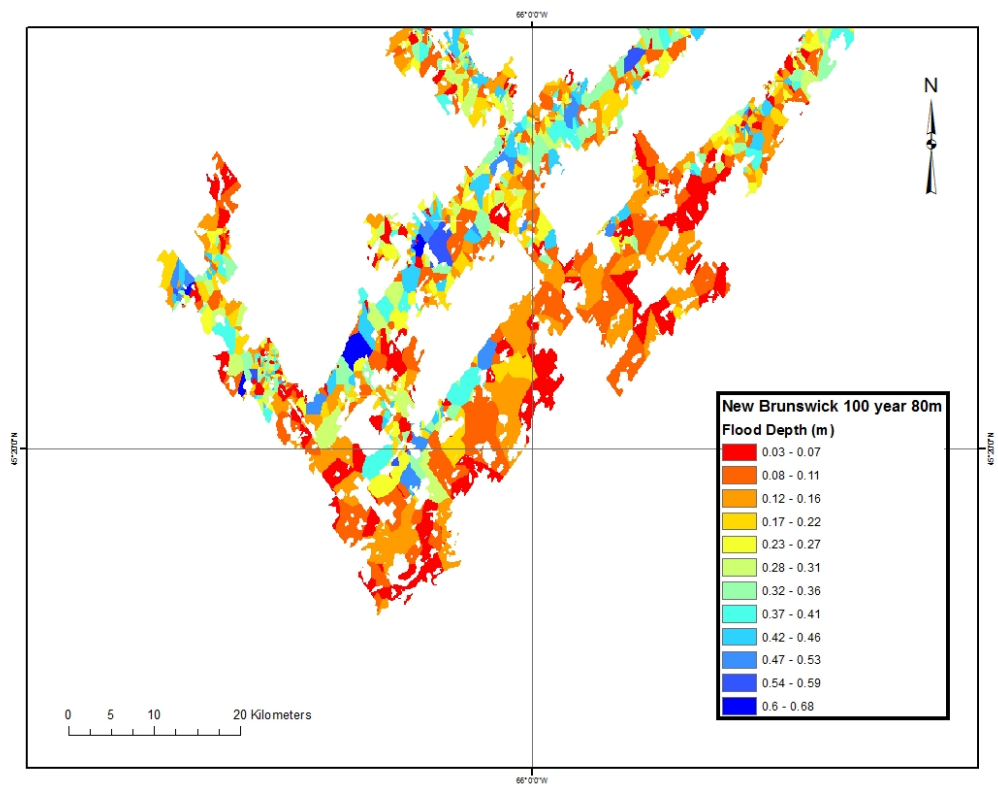
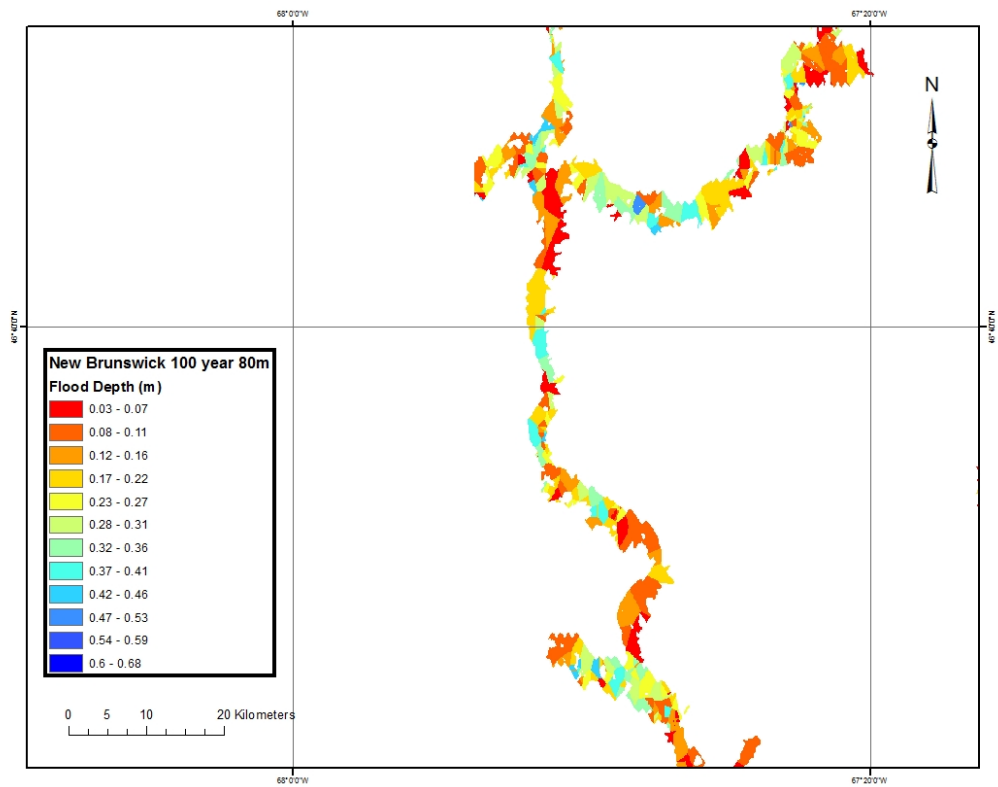
## Appendix D.6: 60m 200 year Floodplain Map



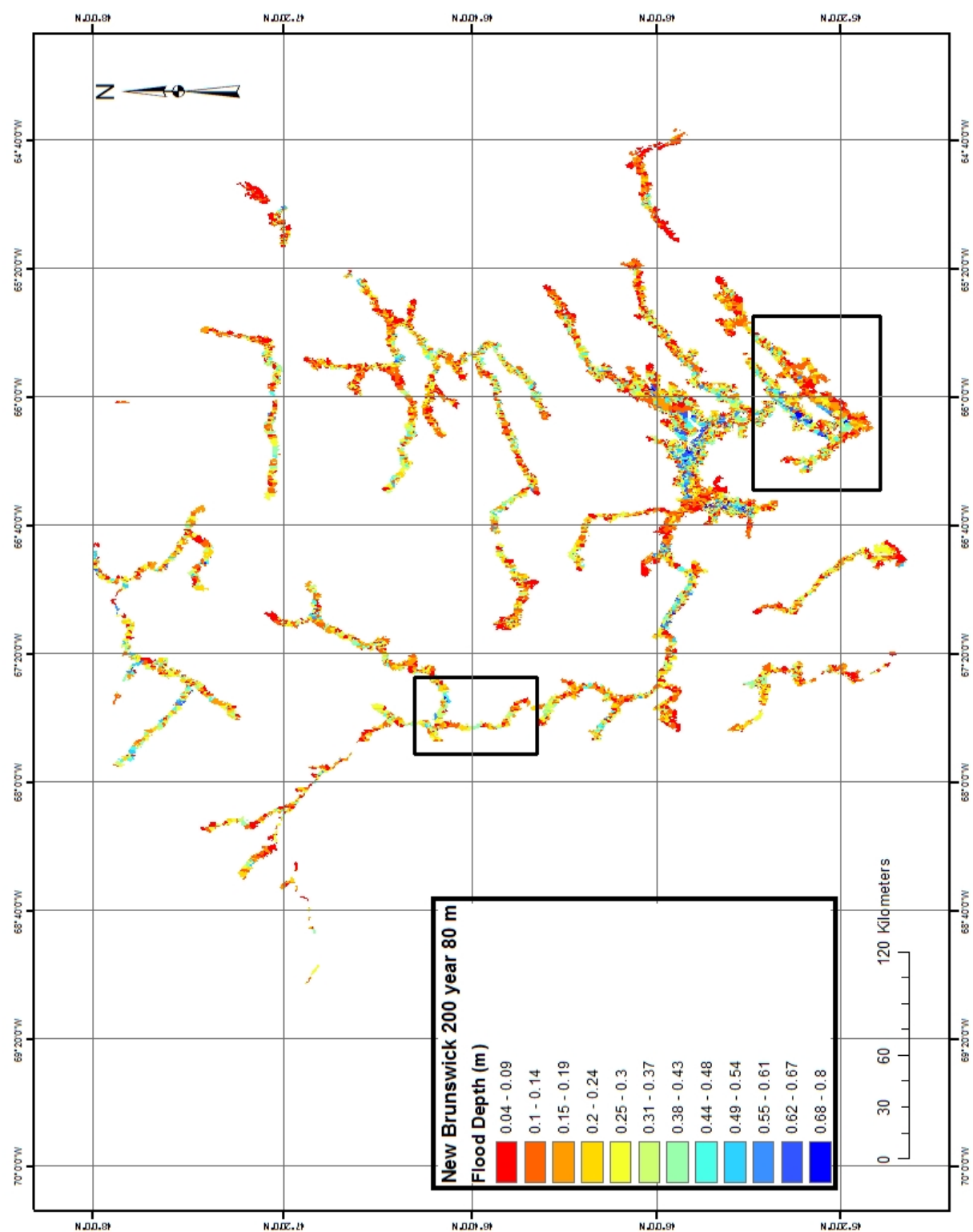


## Appendix D.7: 80m 100 year Floodplain Map

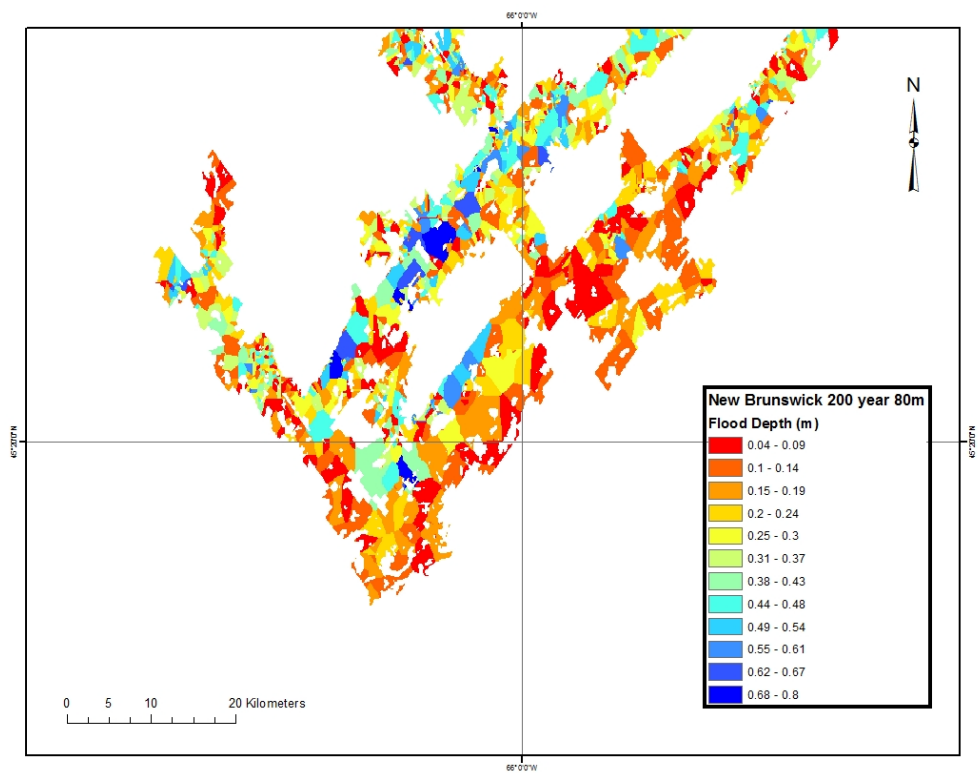
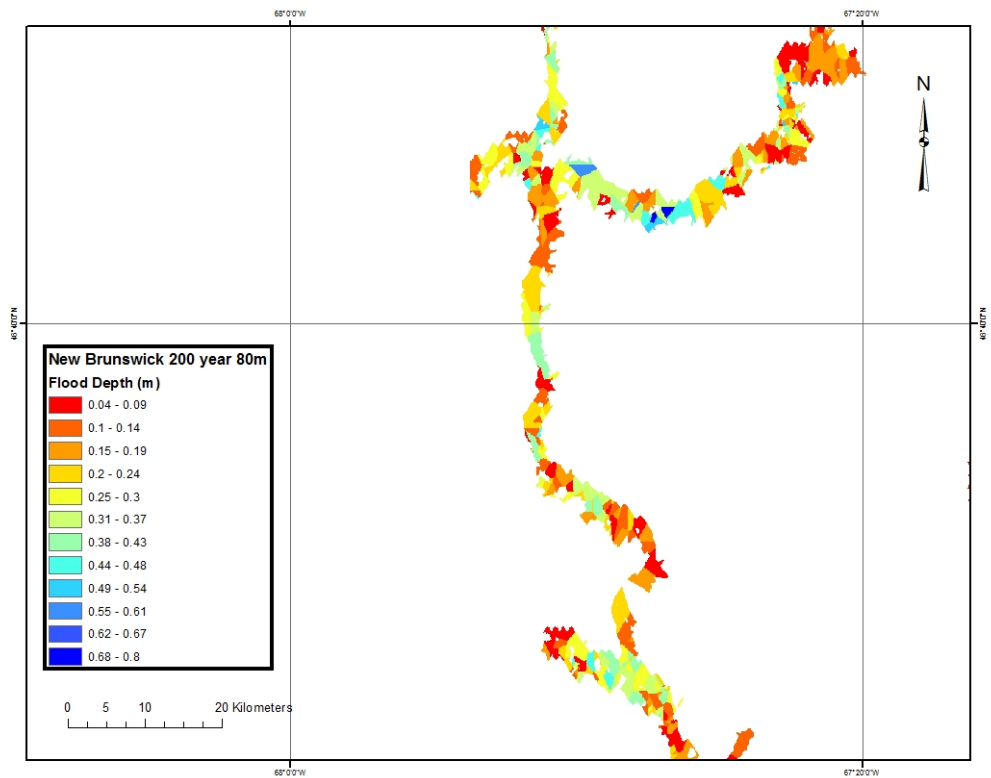




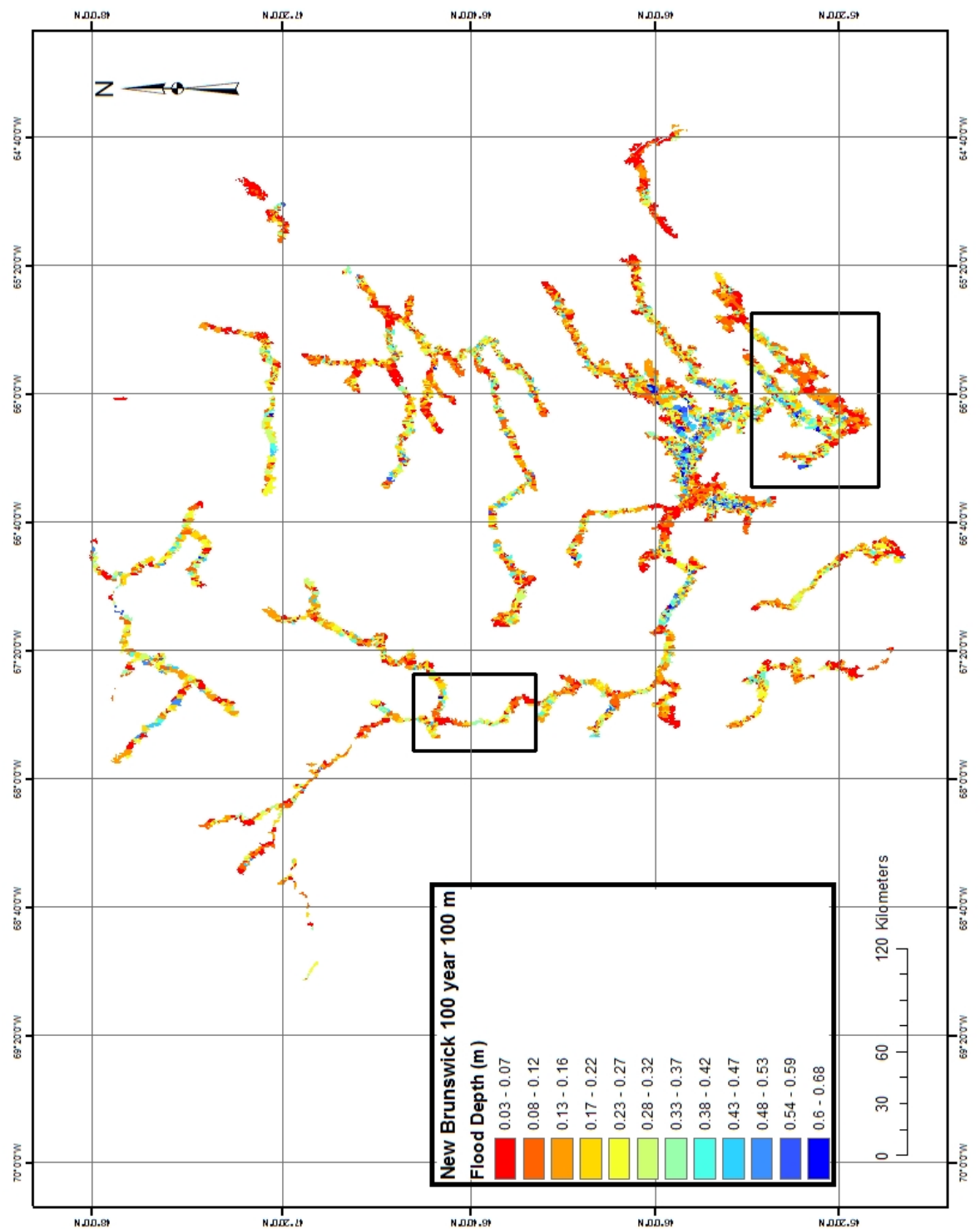
Appendix D.8: 80m 200 year Floodplain Map

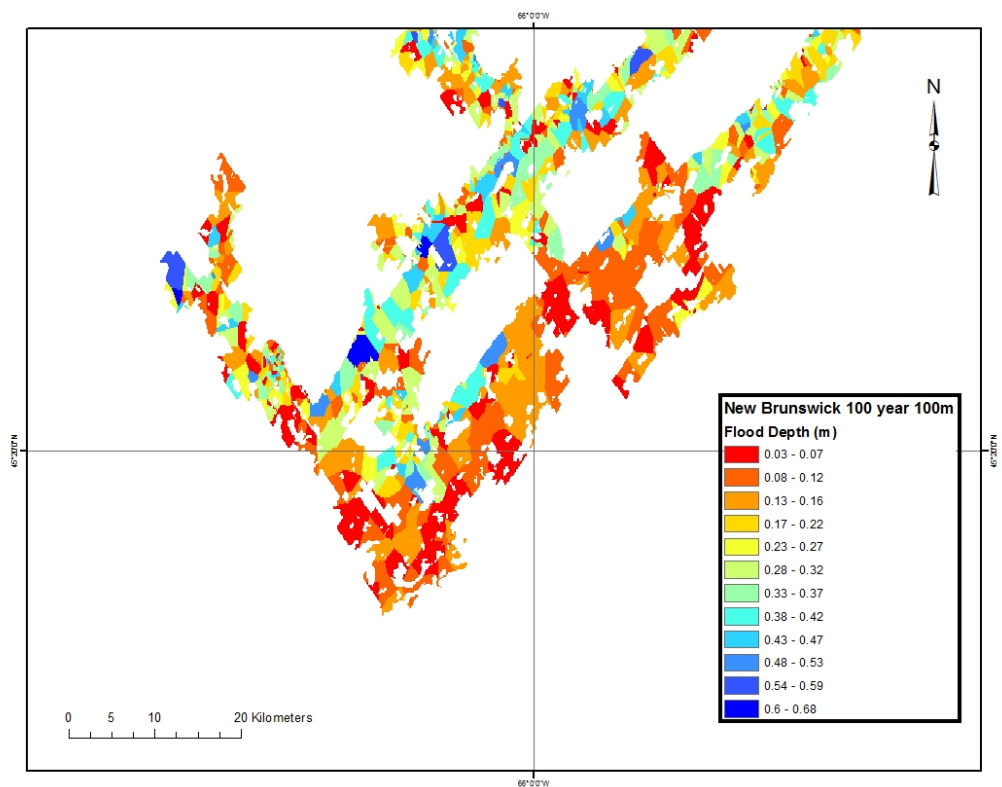
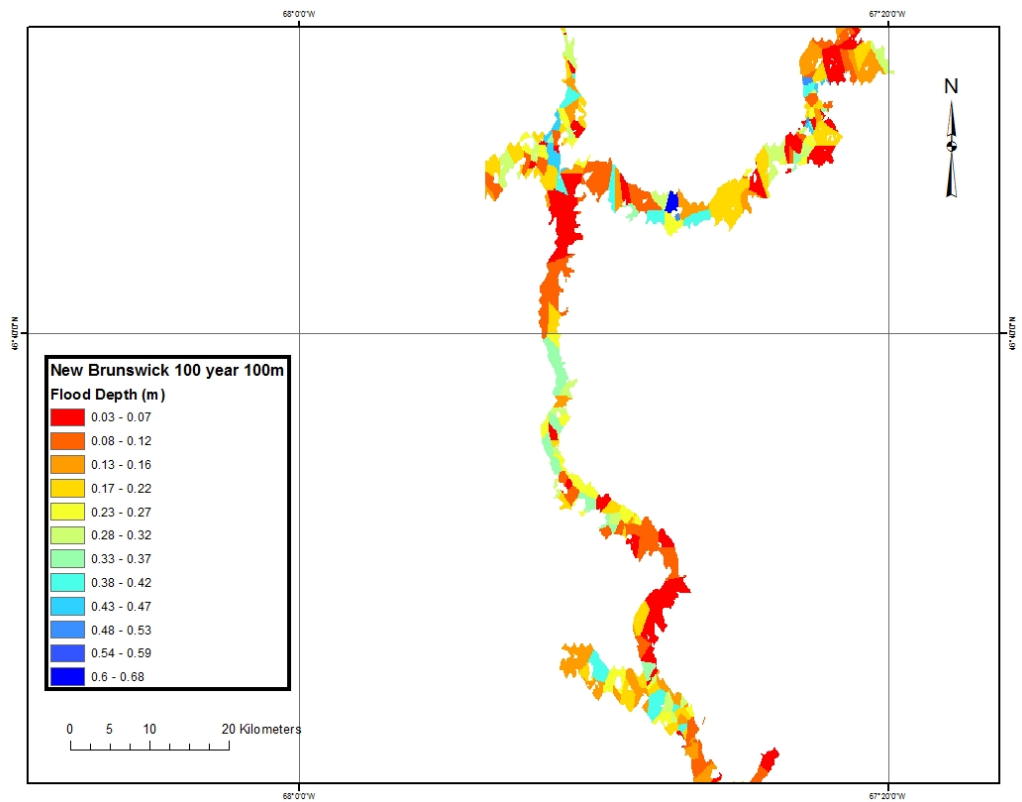




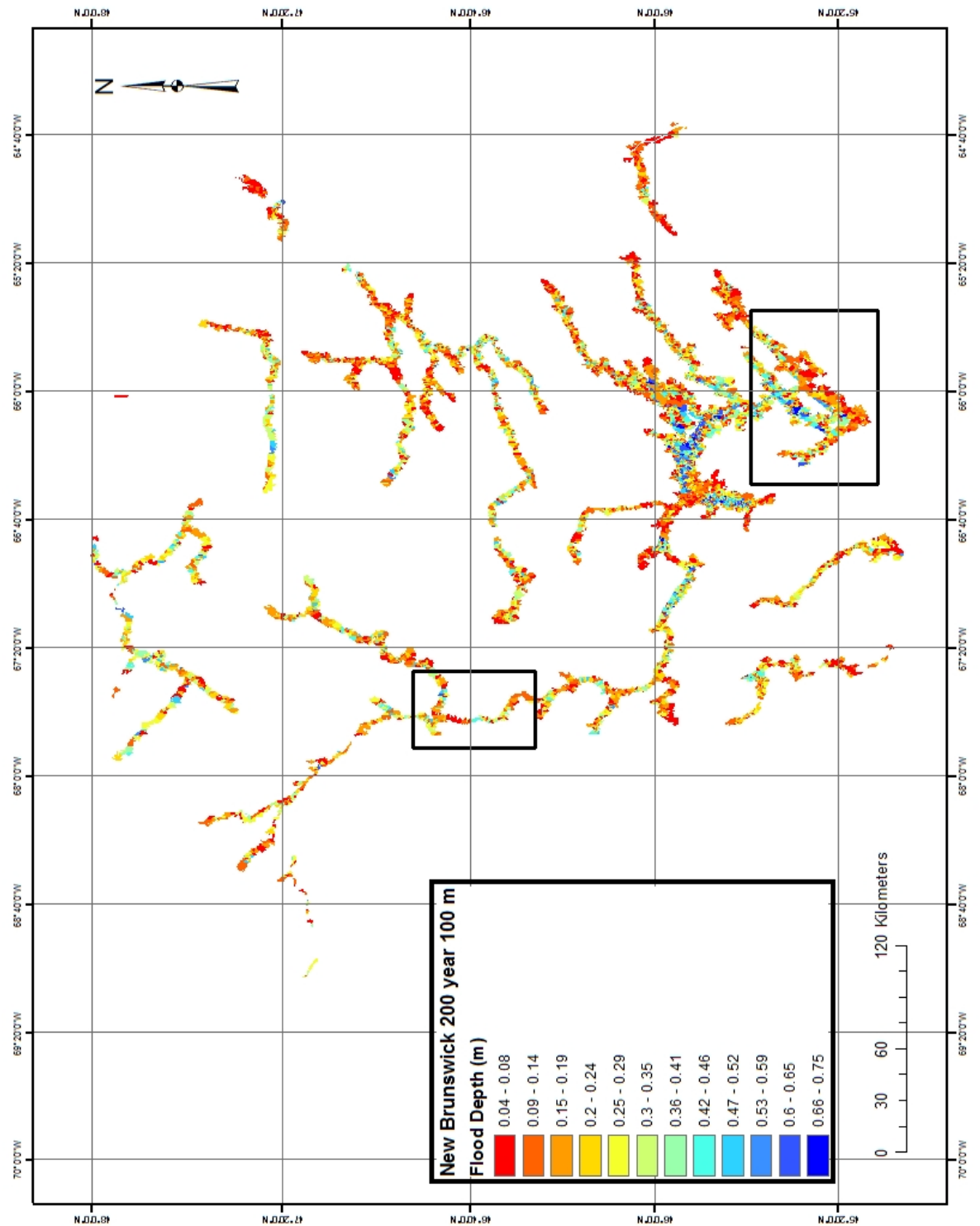


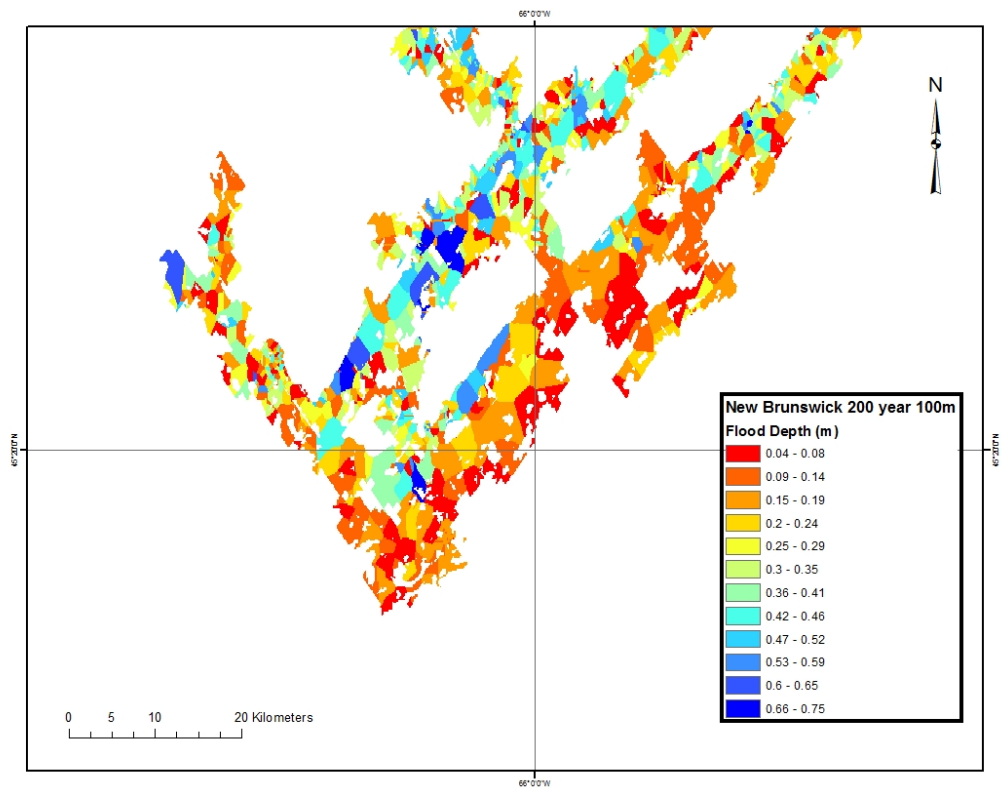
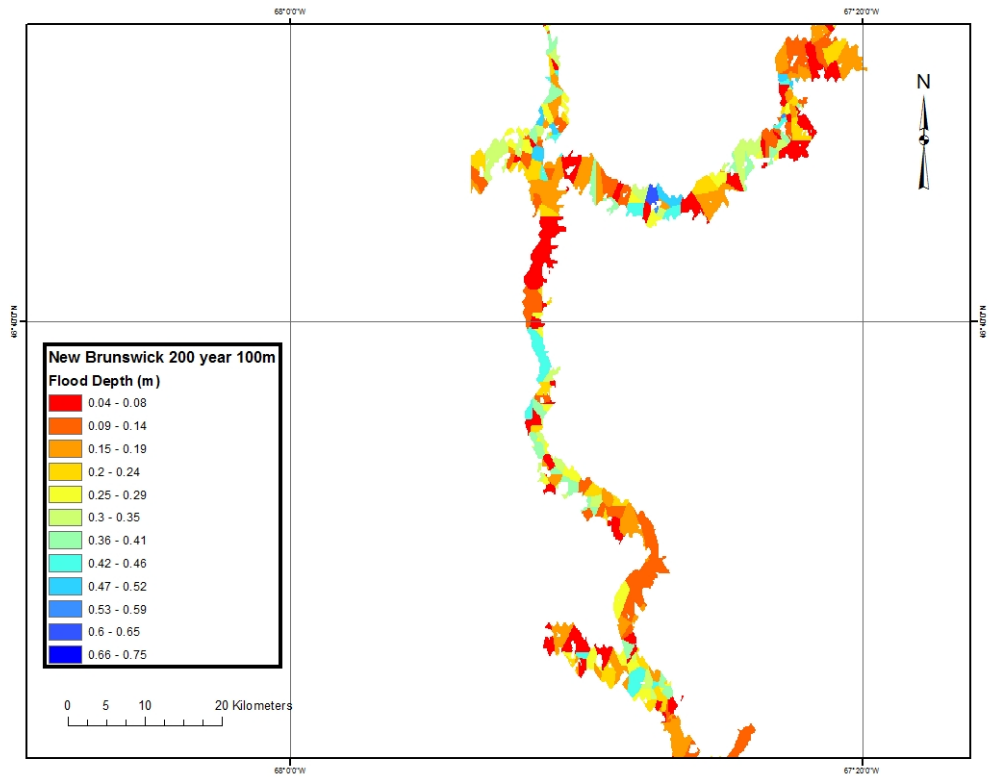
## Appendix D.9: 100m 100 year Floodplain Map



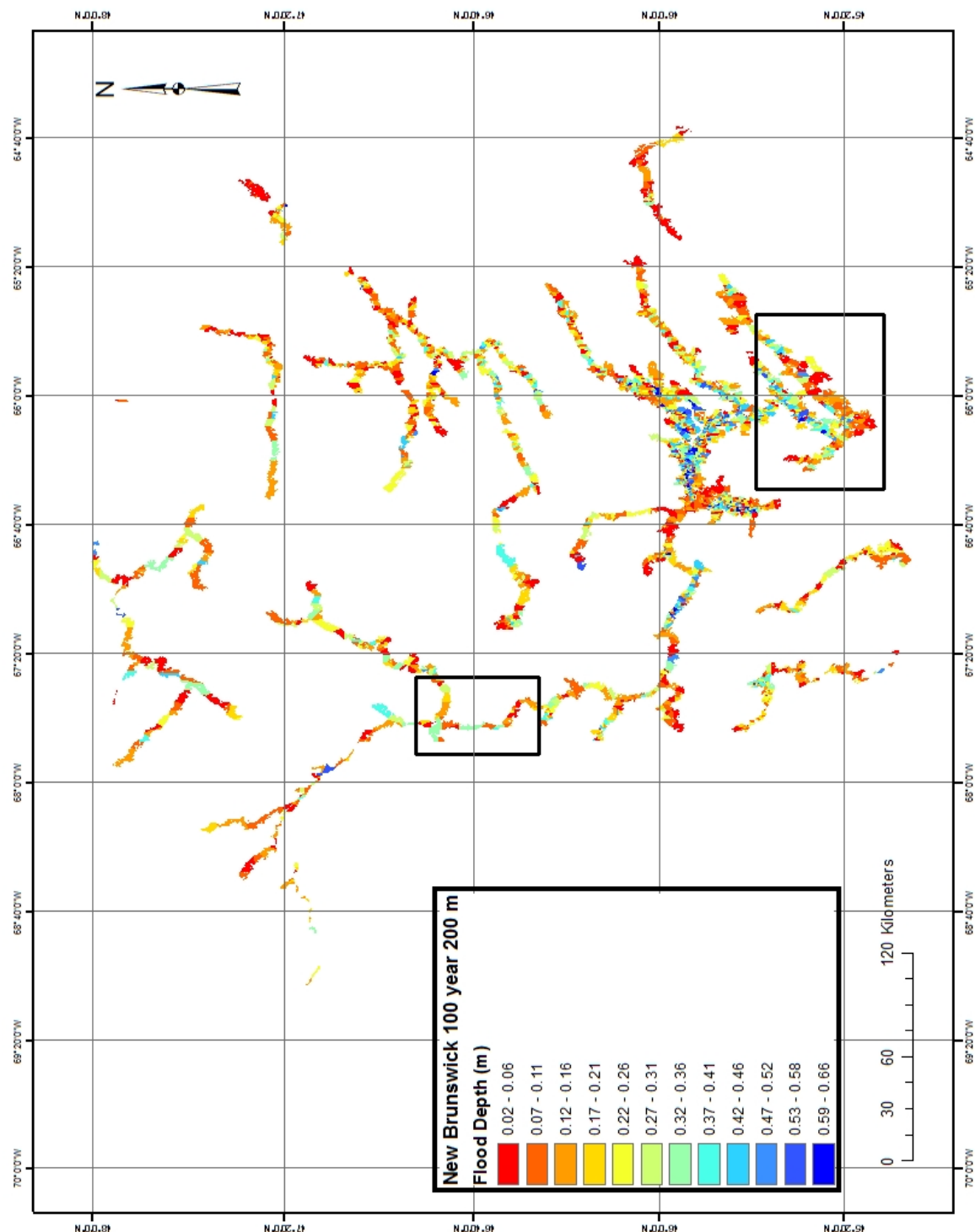


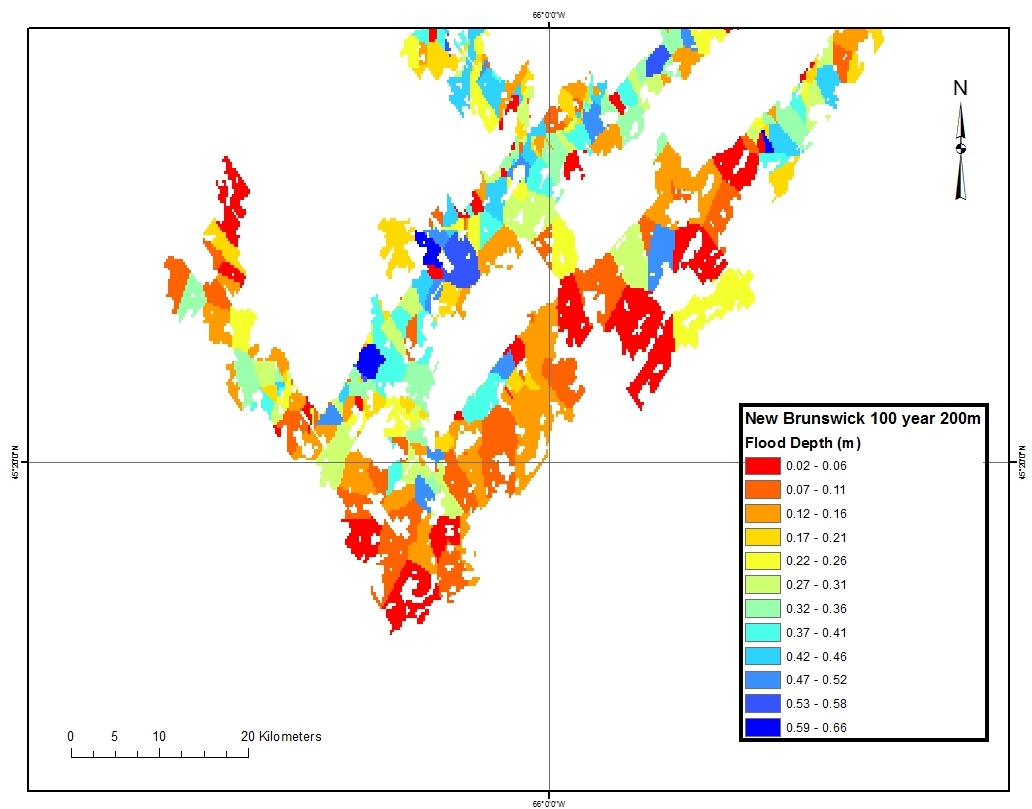
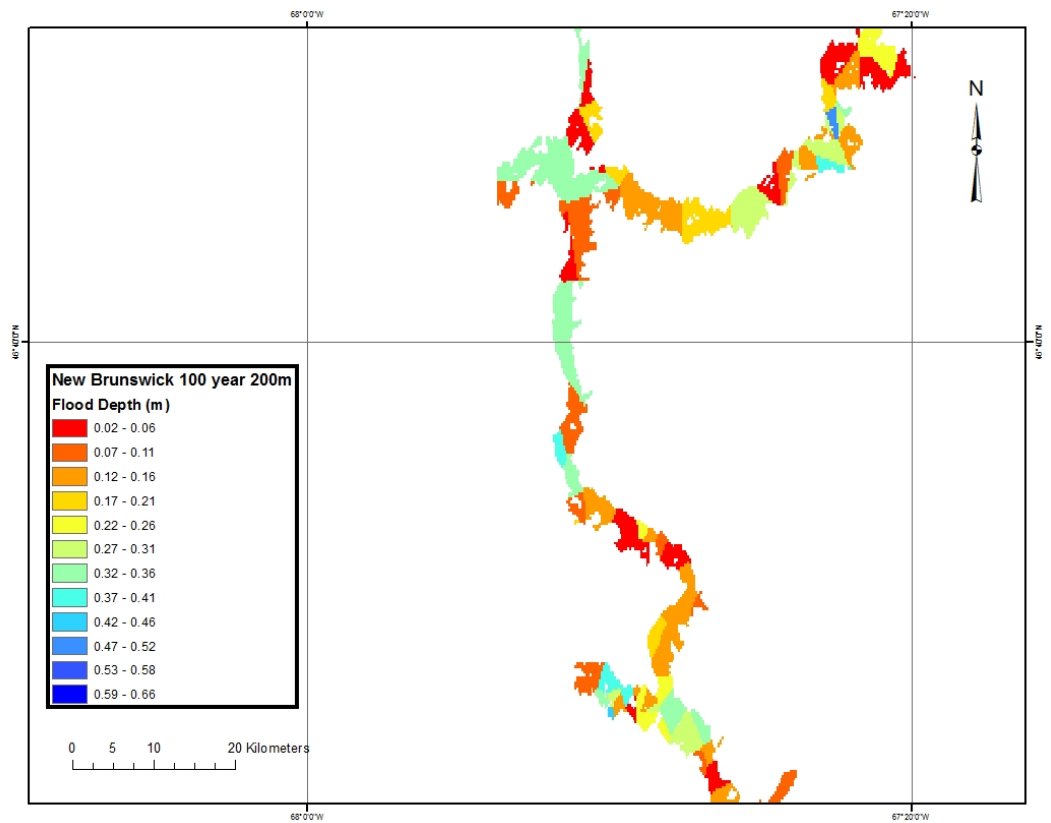
## Appendix D.10: 100m 200 year Floodplain Map



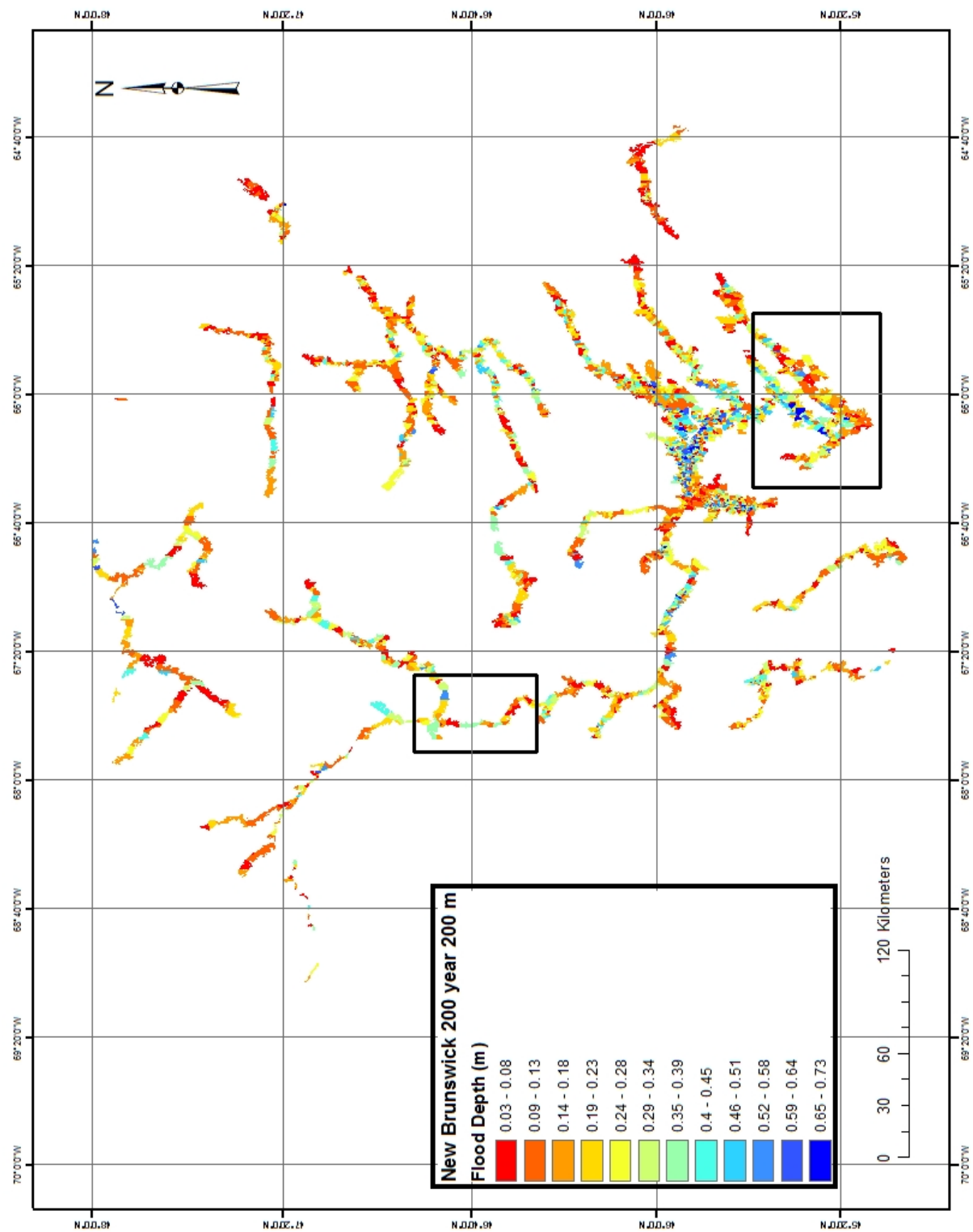


Appendix D.11: 200m 100 year Floodplain Map

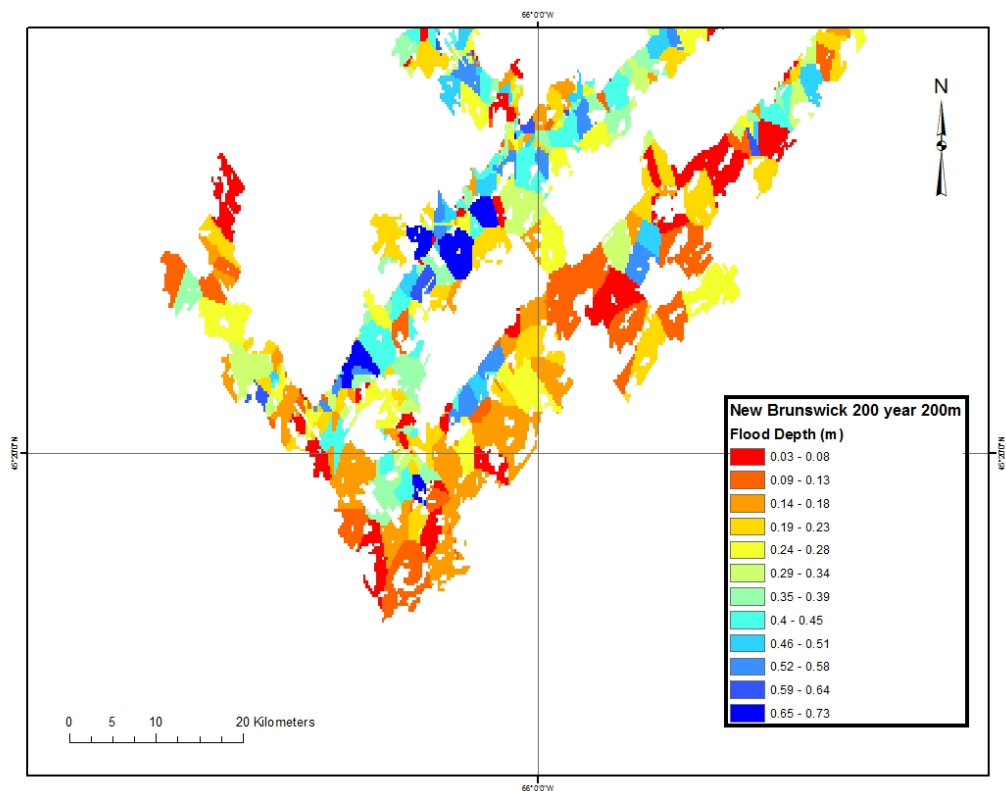
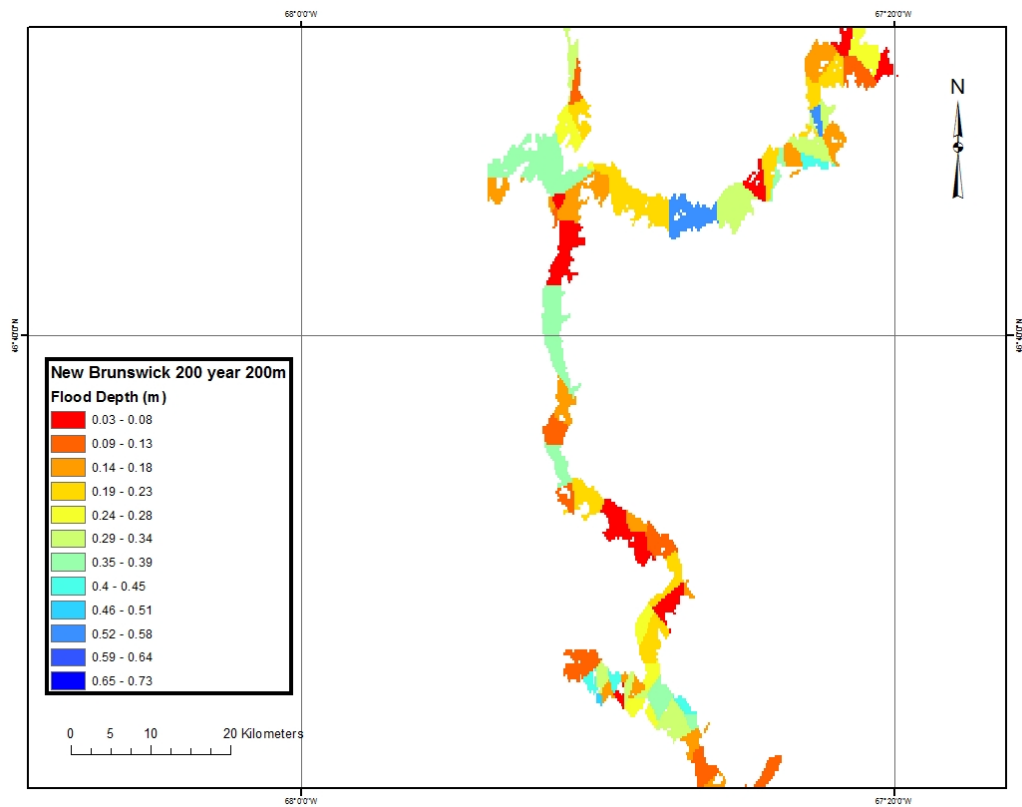




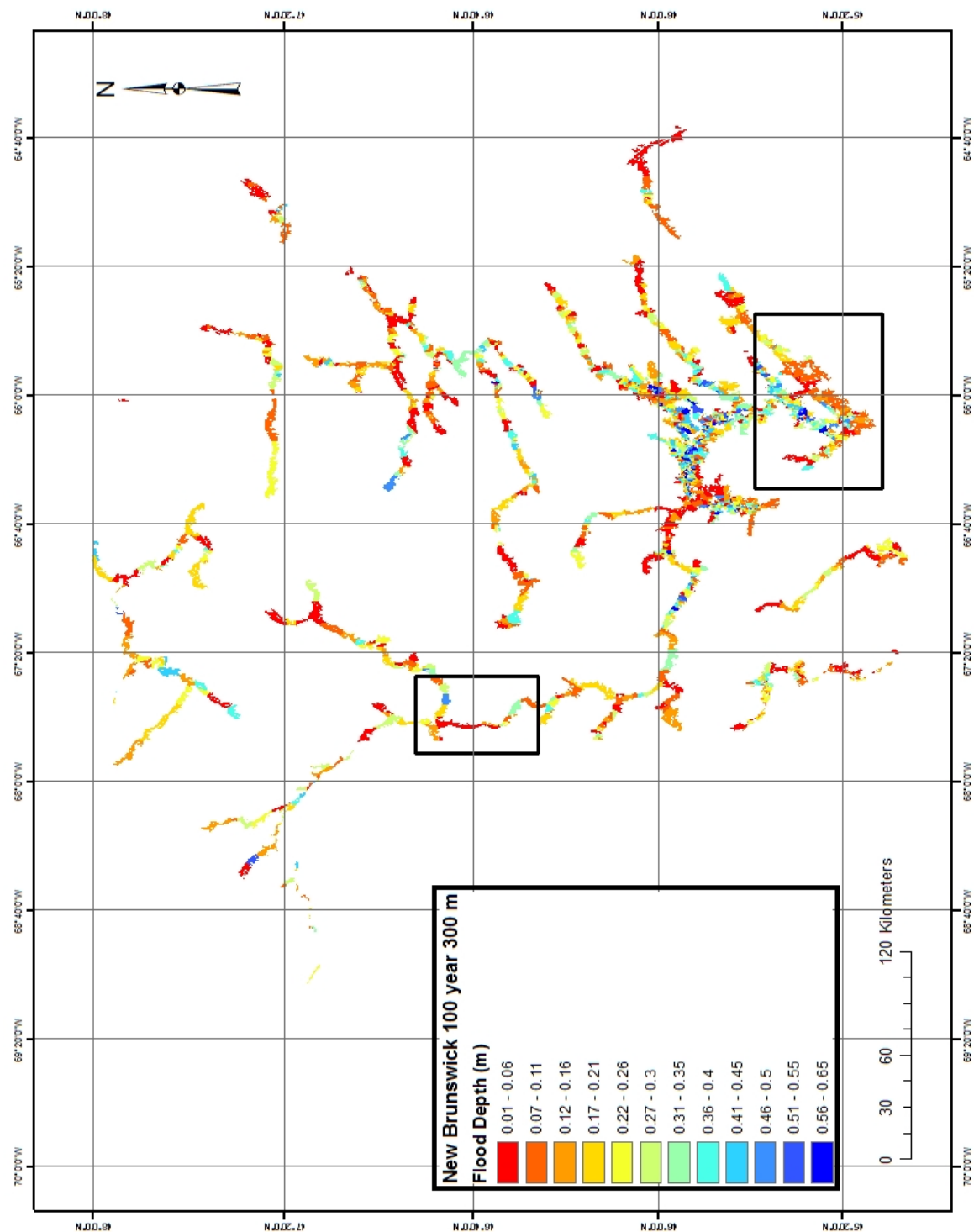
Appendix D.12: 200m 200 year Floodplain Map

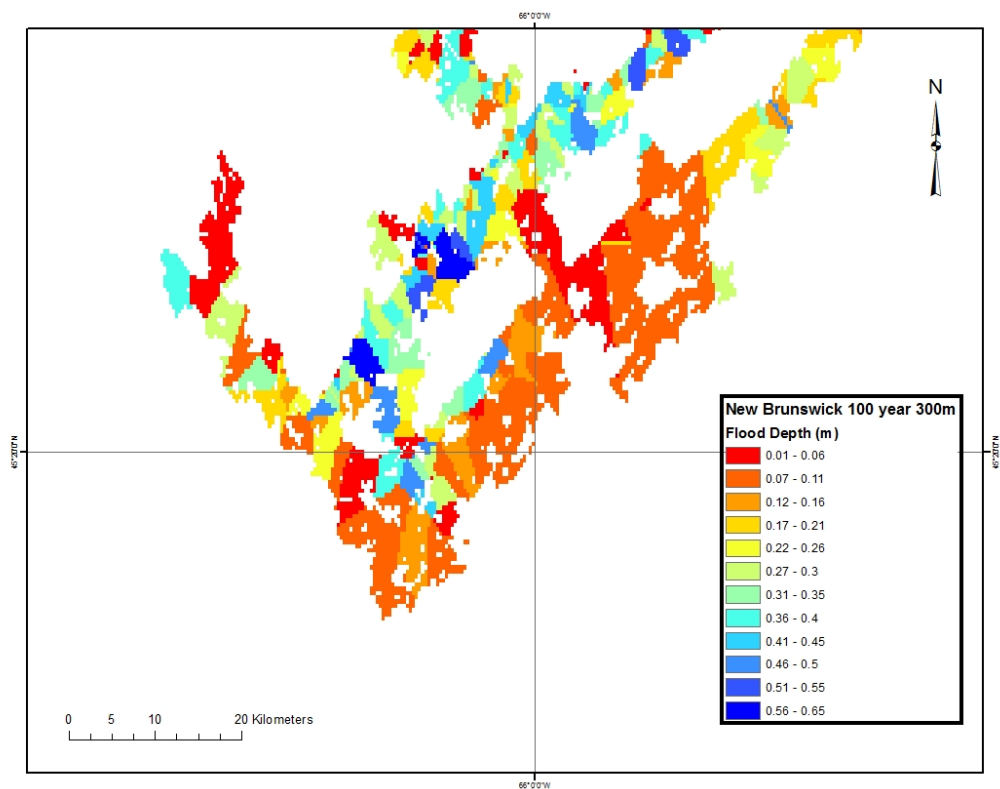
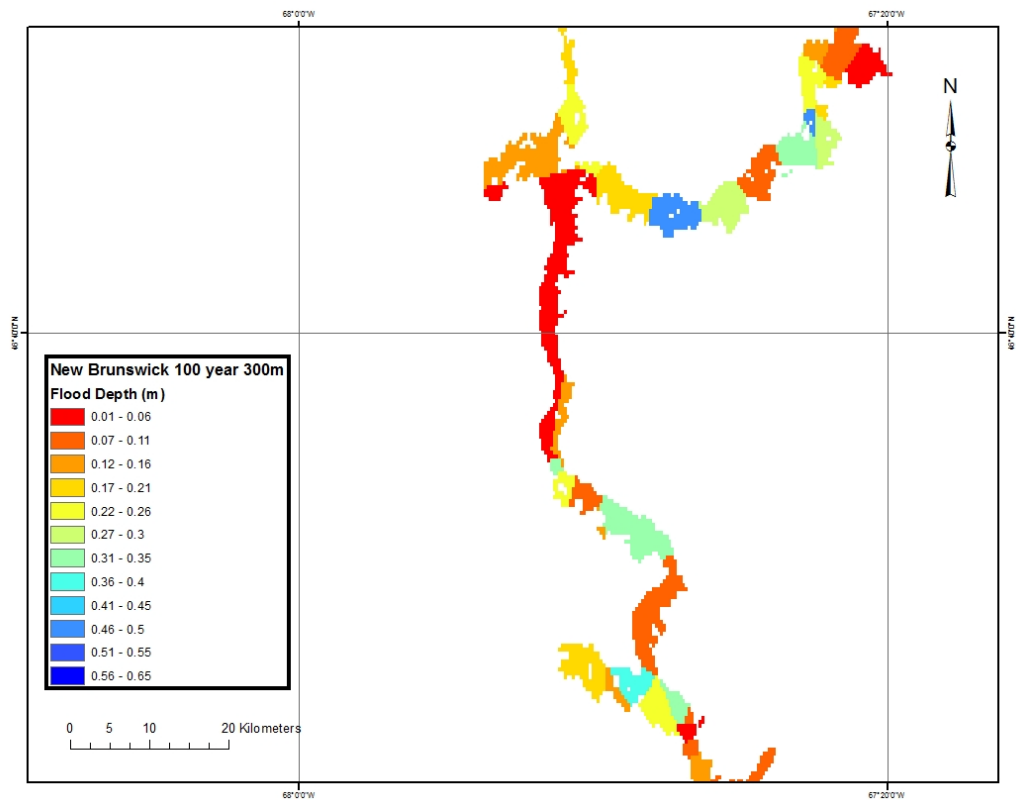




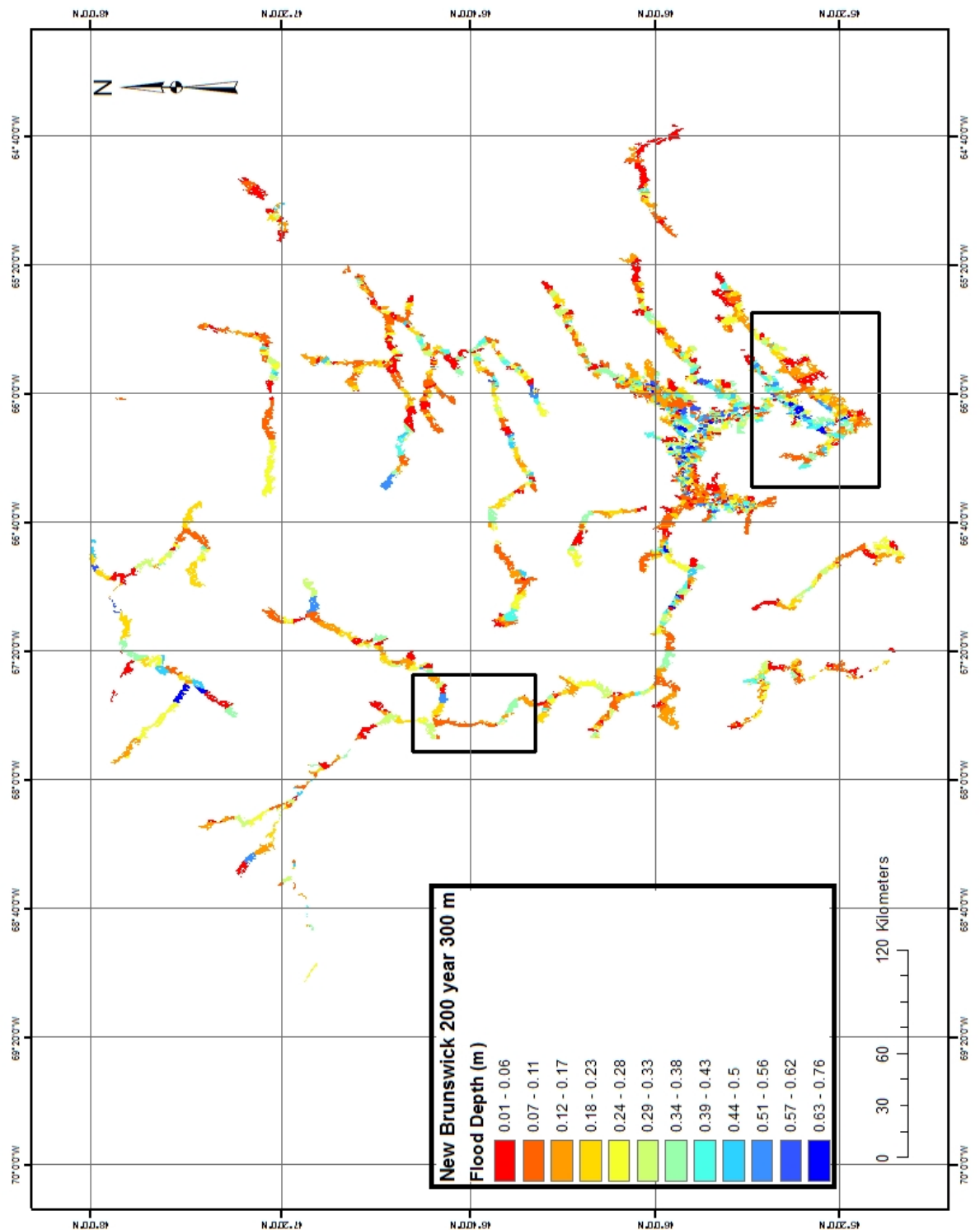


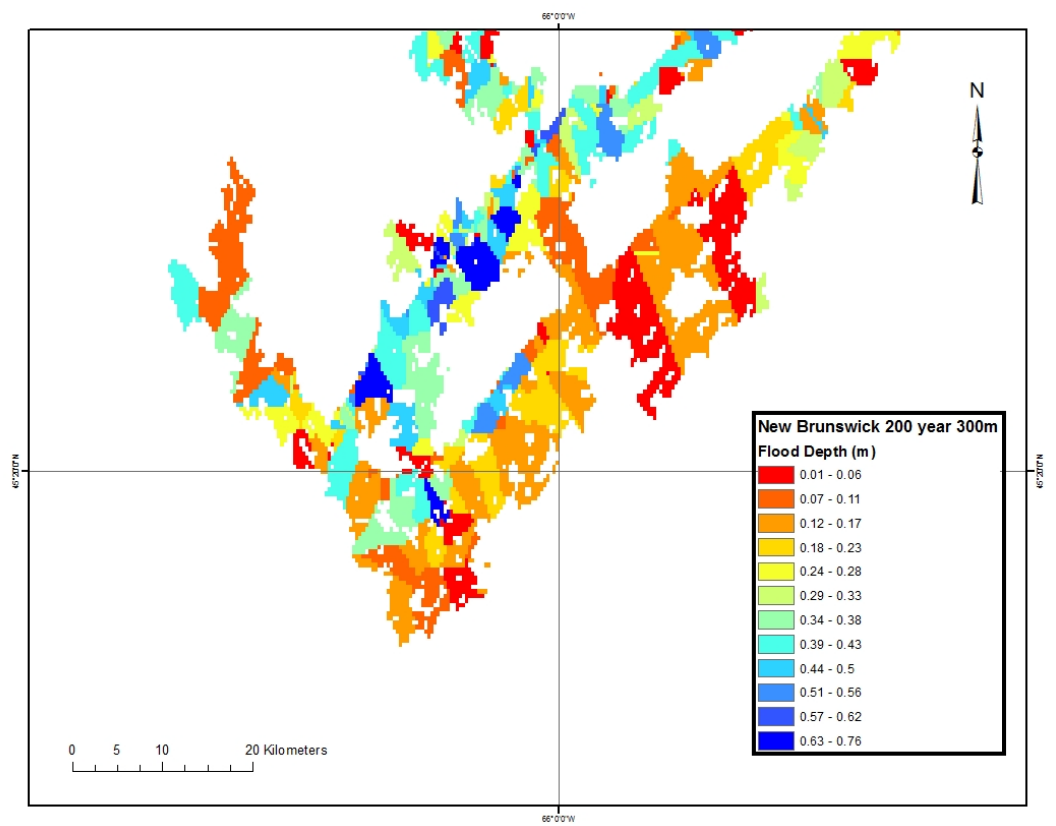
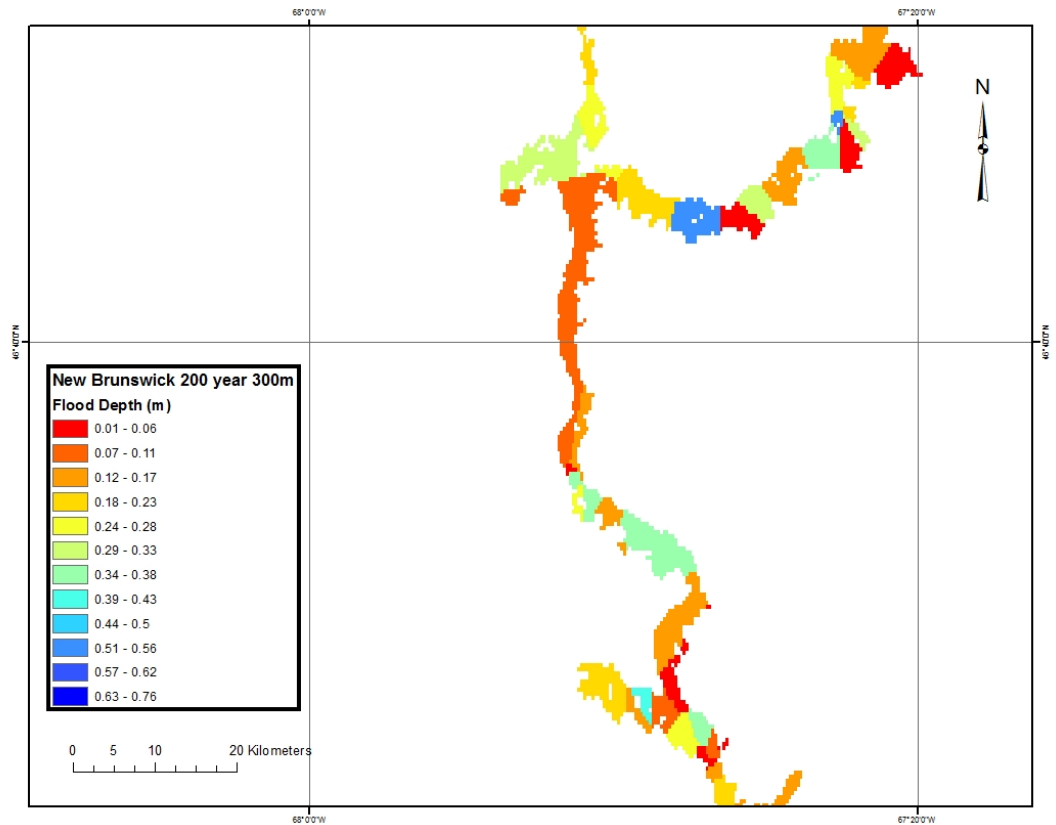
Appendix D.13: 300m 100 year Floodplain Map



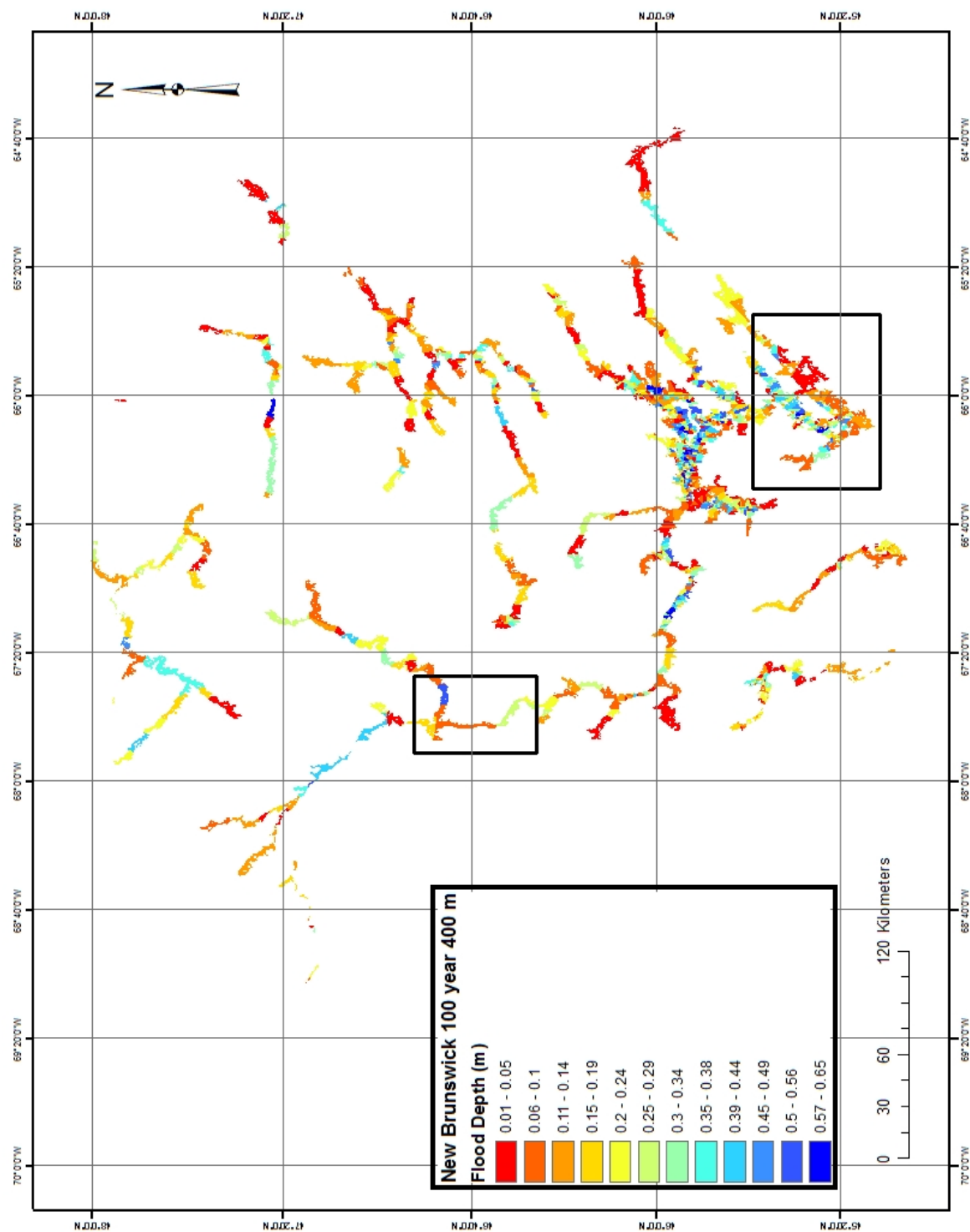


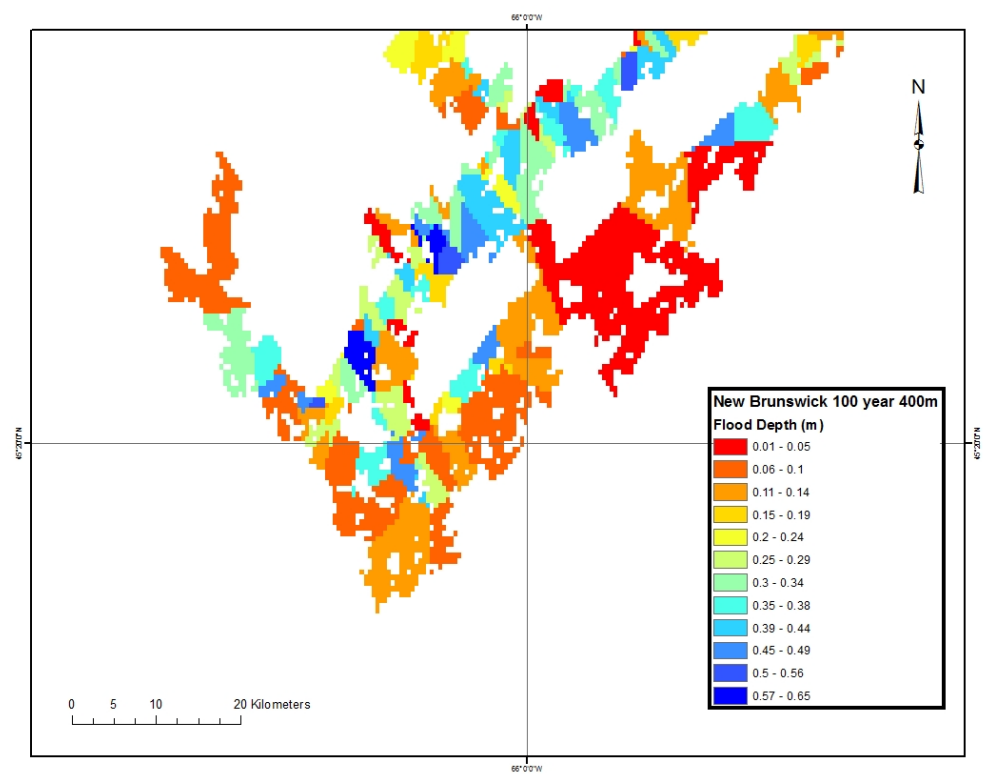
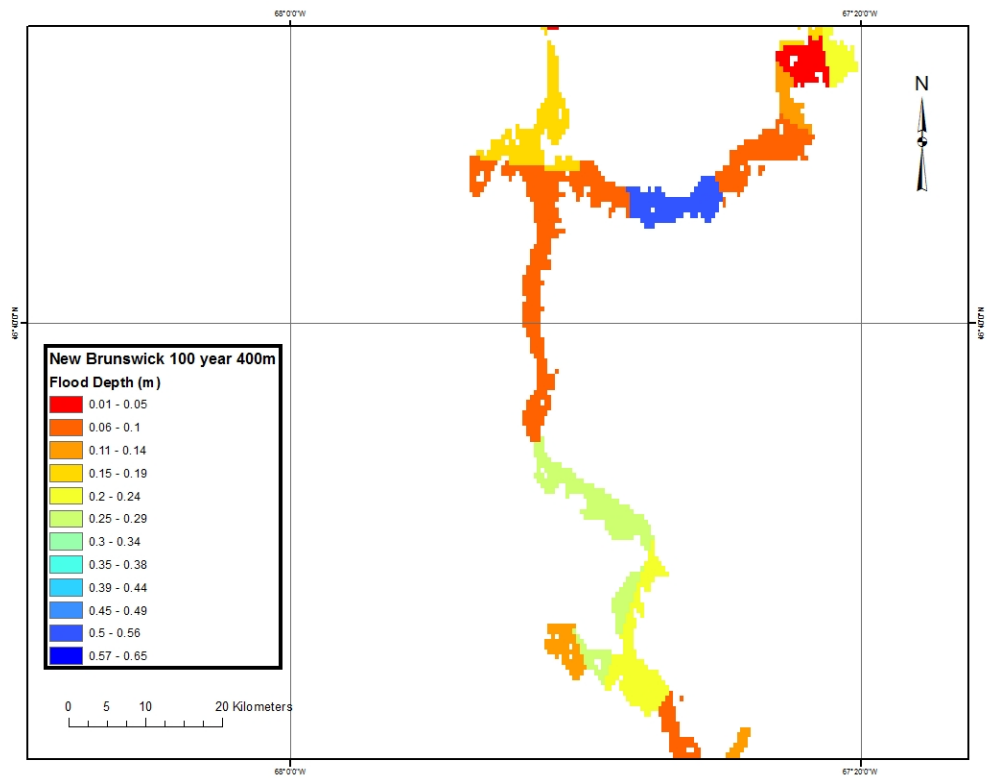
## Appendix D.14: 300m 200 year Floodplain Map



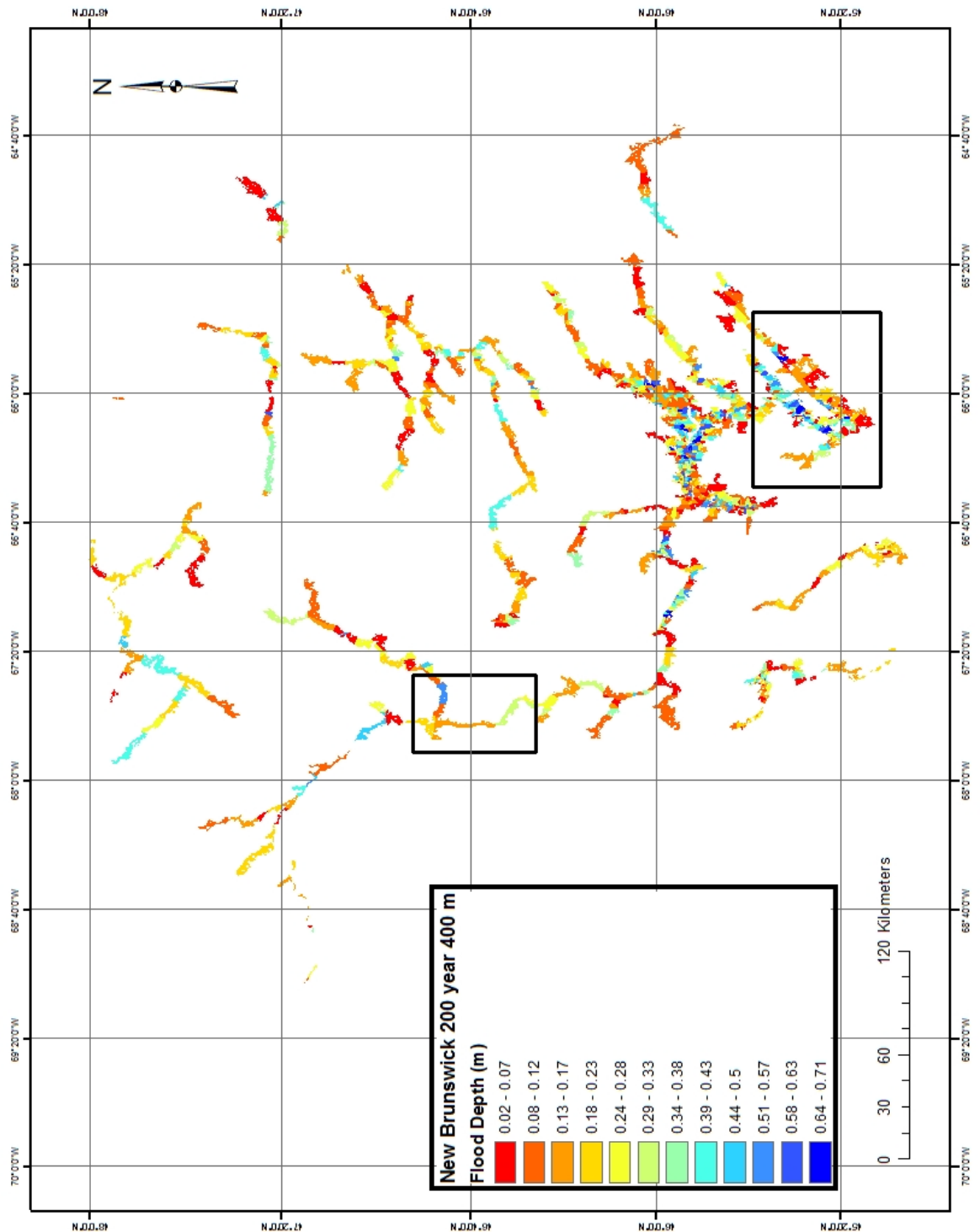


Appendix D.15: 400m 100 year Floodplain Map

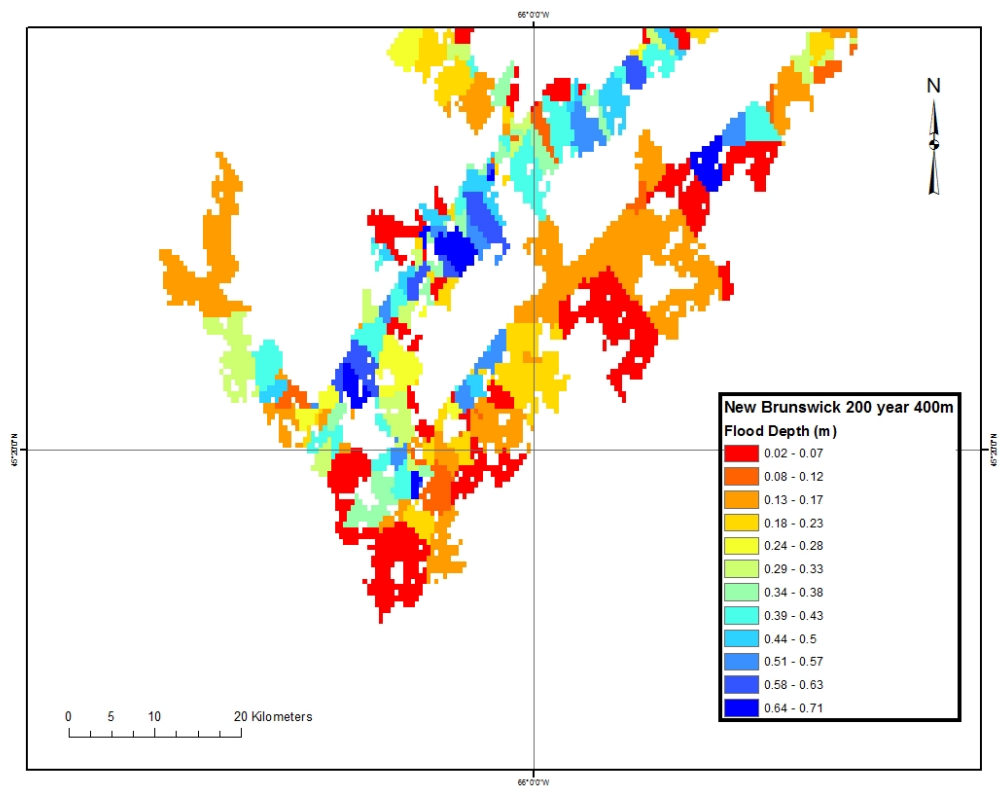
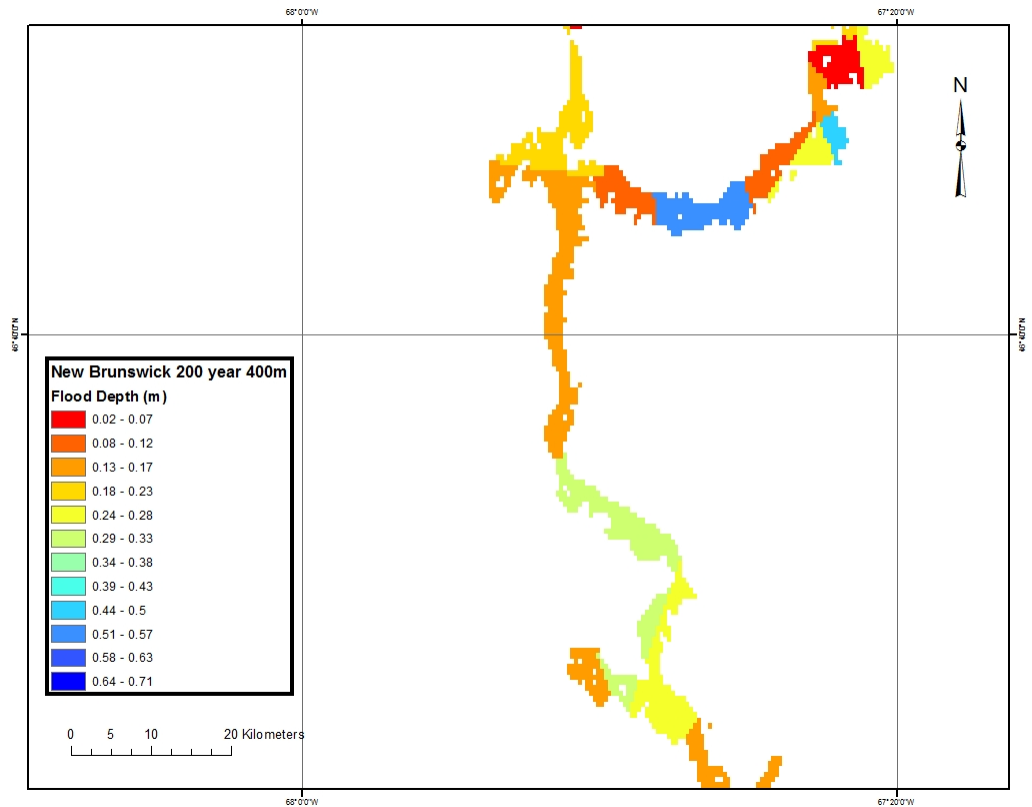




## Appendix D.16: 400m 200 year Floodplain Map







## Curriculum Vitae

**Name:** James Eric Braden

**Post-Secondary** Western University

**School Education:** London, Ontario, Canada  
2019 B.E.Sc. Civil and Environmental Engineering

**Work Experience:** Teaching Assistant (Engineering Statics, Engineering  
Communications, Engineering Ethics)  
Western University  
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2019-2021

**Publications:** James Braden and Slobodan P. Simonovic (2020). A Review of Flood Hazard Mapping Practices across Canada. Water Resources Research Report no. 107, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 64 pages. ISBN:978-0-7714-3144-9.